A SYSTEM

OF

ELECTROTHERAPEUTICS

AS TAUGHT BY

THE INTERNATIONAL
CORRESPONDENCE SCHOOLS

SCRANTON, PA.

VOLUME I

ELECTROPHYSICS

DIRECT CURRENTS ELECTROSTATICS
MAGNETISM AND ELECTROMAGNETISM
ESSENTIAL APPARATUS
WITH PRACTICAL QUESTIONS AND EXAMPLES

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PREFACE.

The Electrotherapeutics Course of The International Correspondence Schools, of Scranton, Pa., comprises twelve Instruction Papers. These Instruction Papers are issued in bound volumes and in pamphlets. In this latter form they are supplied to students to study as they proceed through the Course. The bound volumes will make a desirable acquisition to any medical library, and will always serve as a ready means of reference. The Instruction Papers are bound in paper, so that the student can carry one in his pocket and study the whole or part of it, as his time permits. This usage must necessarily show itself in the appearance of the Instruction Papers; a page may become soiled, torn, or even lost. For this reason, the bound volumes will be appreciated by the student for library work, and may be consulted by him years after he has completed his Course.

The method of numbering the pages, cuts, articles, etc., is such that each Paper and part is complete in itself; hence, in order to make the indexes intelligible, it was necessary to give each Paper and part a number. This number is placed at the top of each page, on the headline, opposite the page number; and to distinguish it from the page numbers it is preceded by the printer's section mark §. Consequently, a reference such as page 29, § 3, would be readily found as follows: The back stamp on each volume shows the sections (i. e., Papers) included in the volume, that for Vol. I reading §§ 1–4; hence, look in Vol. I along the headlines until § 4 is found, and then through § 4 until page 29 is found.

The Question Papers are given the same section numbers as the Instruction Papers to which they belong, and are grouped together at the end of the volume containing the Instruction Papers to which they refer. The paging of each Question Paper begins with 1, as in the case of the Instruction Papers.

Vol. I contains four Instruction Papers on electrophysics, in which all facts and principles of electrophysics are fully, clearly, and concisely set forth, and illustrated wherever illustration is necessary to make the text clearer to the student. These Papers on electrophysics were written by experienced electrical engineers, employed in the Electrical Engineering Department of THE INTERNATIONAL CORRESPONDENCE SCHOOLS, under the direction of W. F. Brady, M. D., Professor of Genito-Urinary Surgery, and Dean of the Faculty of the The Correspondence School of Electrotherapeutics. They were afterwards edited by Augustin H. Goelet, M. D., Professor of Gynecology and Abdominal Surgery, of the New York Clinical School of Medicine, and S. H. Monell, M. D., Chief Instructor of the New York School of Special Electrotherapeutics.

Vol. II contains four Papers on the physiology of the different electric currents and the technique of their application, which were written by W. F. Brady, M. D., and afterwards revised by Drs. Goelet and Monell.

Vol. III contains two Papers, one on the therapeutic uses of electricity in gynecology, written by Augustin H. Goelet, M. D., the other on the therapeutic uses of electricity in the medical and surgical diseases of the genito-urinary system, written by W. F. Brady, M. D.

Vol. IV contains two Instruction Papers, one on the therapeutic uses of electricity in diseases of the nervous system, written by W. J. Herdman, M. D., LL. D., Professor of Diseases of the Mind and Nervous System, of the University of Michigan, the other on the therapeutie uses of static electricity, written by S. H. Monell, M. D.

Each Instruction Paper is accompanied by a series of questions covering in a most exact manner the text in question. The Course has been prepared especially for doctors, dentists, students, and nurses, and the application of the three electric currents in the treatment of diseases has received constant attention from the writers of our Papers. Electrodes and technique of electrieal applications are illustrated and fully described in the Papers treating of the diseases in which they are used.

THE INTERNATIONAL CORRESPONDENCE SCHOOLS.

CONTENTS.

DIRECT CURRENTS.

DIRECT CURRENTS.

NATURE OF ELECTRICITY.

1. Electricity an Exact Science.—It has often been remarked that "electricity is a mystery"; so it is, and so too are gravitation, heat, and light, for in none of these cases is it known exactly in what manner the energy acts on matter. But this does not make the science of these forces any less exact, nor does it necessarily mean that we are fumbling in the dark, nor that the laws of these phenomena may be upset at any moment by new discoveries.

Nobody may say that astronomy is not an exact science; and yet the origin of that force upon the action of which all astronomical laws are based is yet to be explained. Notwithstanding all this, it has been possible to determine years ahead the transit of the planets, and within the fraction of a second. Nevertheless, our knowledge of the force of gravitation is far more limited than our knowledge of electricity. In the latter instance, it is possible to at least establish a current, to conduct it, and to regulate it at will. It is also possible to study the action of the current in all its possible combinations, and new discoveries are continually bringing us nearer to the solution of the question, "What is electricity?" Not so with gravitation; while great progress has been made in other sciences, our knowledge about the inner nature of gravitation is no further advanced than it was ages ago, and no immediate progress is in view.

As with gravitation, so it is with electricity; ignorance of its nature has not prevented the study of its action, and very exact

laws have been established. By means of these laws we are enabled to predict beforehand, and without fail, what will take place under certain prearranged conditions.

2. Electrification.—The expression "producing electricity" is erroneous. We can produce a pressure that will cause electricity to flow, but we cannot produce electricity itself. Electricity can only be transferred from one place to another, and does not in itself represent energy—any more so than water or air. Air in motion or under pressure does possess energy, and the same holds true with electricity. To electrify a substance, work has to be performed; *electrification*, therefore, is a form of energy, and work will again be performed before the substance returns to a neutral state. It is perhaps nearer the truth to say that electricity is a peculiar state of matter, a certain condition of the *ether*.

3. The Ether.—The ether is a medium supposed to pervade all space; it is supposed to possess inertia, and to be able to move without friction. We must consider it the one universal medium, and that by its means all actions between separate bodies are carried on. In brief, its function is to act as a transmitter of motion and energy. The ether must no longer be considered merely as a possibility, a convenient subterfuge for the explanation of certain phenomena. On the contrary, the existence of such a medium has beyond a doubt been proved by recent researches; even its density and its rigidity have been calculated and the calculations verified by experiments. It is no longer a question of its existence, but rather of its constitution.

Light, heat, electricity, and magnetism are all supposed to be transmitted through space by some active condition of the ether, either in the form of longitudinal or of horizontal vibrations.

If a bell is vibrating in a glass vessel, the sound can be heard from the outside; but if the vessel is put in communication with an air-pump and exhausted, the sound grows fainter and fainter as the vacuum increases, showing that the sound needs the air for its transmission. We find that a magnet enclosed in a glass vessel is just as active when the vessel is exhausted

as when it is not. The filament of an incandescent lamp, although it glows in a vacuum, is visible from the outside of the globe, proving that air is not necessary for the transmission of light. Perhaps it may not be necessary to go further into the manifestations of the ether, yet more proofs of its existence may be given. For instance, the sun's rays of heat and light are transmitted through space, where it would be impossible for them to travel without the presence of some such medium as ether. It has also been noticed that an increase in the number of visible spots on the surface of the sun has a marked influence on magnetic needles, proving that the force of magnetism or electricity also travels through an apparently empty space. We must imagine the ether as all-pervading, as not alone *surrounding* material bodies, but *penetrating* through their interiors; that it, in fact, encircles the smallest particles, even the molecules and atoms.

Formerly, the phenomena of heat, of light, of magnetism, and of electricity were all supposed to be actions of fluids; even today we speak of *currents* of electricity and of magnetism. This must not be taken too literally. It is more than likely that there is no flow existing, but simply a vibratory action. For instance, we do not speak of a current of heat; when we therefore speak of electricity or magnetism as flowing, it is done more because of the facility it offers to explain the action of the various phenomena than because of a belief in the actual existence of a current.

ELECTRICAL UNITS.

THE VOLT.

4. Electromotive Force.—We have now seen why the expression "producing electricity" is misleading, just as it is incorrect to speak of producing a current of water. In each case there is produced a pressure somewhere in the circuit, and this is again the primary cause of setting the water or electricity in motion. There is no exception to this; an electric current will never be established without a pressure having been first

created, and even then a current will not flow unless other conditions are such as to permit it.

Fig. 1 will illustrate this more fully. *A* and *B* are two tanks partly filled with water and connected by the tube *C*. If the water is on the same level in each tank, as indicated by the full lines, it will be at rest and have no tendency to flow in either direction ; but if the tank *B* is raised to the position indicated by the dotted lines, the situation is then changed, and the water has a tendency to again place itself at the same level. There will therefore be a flow from *B* towards *A* until balance is restored. If the water is prevented from flowing, there will still be a pressure in the tube, and this will vanish only when tank *B* is returned to its original position.

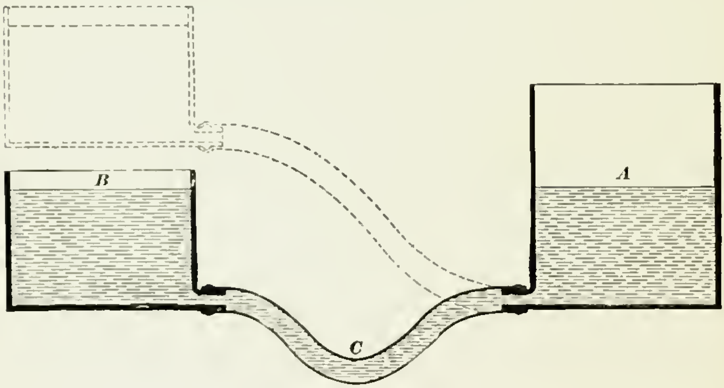

FIG. 1.

The conditions under which an electric current will flow are exactly similar. We see that, so long as the tanks remain in their original position, there is no current and no tendency to start a current, because the pressures exerted by the water-columns in the tanks on the water contained in the tube are exactly balanced. If, however, the tube *C* be disengaged from the tank *A*, water will flow out, because the pressure is greater at one end of the tube than at the other. We can now clearly see that the first requirement necessary to start a current, either of water or of electricity, is to create an excess of pressure somewhere in the circuit, or, in other words, to

create a difference of potential between any two points. In electricity this pressure is called *electromotive force*, *difference of potential*, *pressure*, or *voltage*. Electromotive force is, perhaps, the most frequently used; it is usually abbreviated to E. M. F. A more complete explanation of these terms will be given in a later part of this Course.

5. Available E. M. F.—To make comparisons between various pressures in the water-tube *C*, a unit would be used of, say, so many pounds per square inch. The corresponding electrical unit is the *volt*. By means of the latter unit it would be possible to indicate the surplus of pressure at one end of a conductor over that at the other—in other words, to give the difference of potential, available E. M. F., or pressure.

THE COULOMB.

6. Quantity.—Having discussed the subject of pressure, the next point to be considered is quantity. Evidently, the amount of water that may flow through the tube *C* may vary between limits very far apart; it will be necessary to know

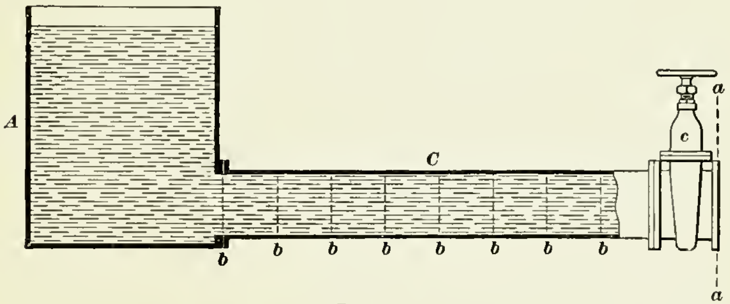

FIG. 2.

how much water has been flowing, and to agree on some unit as a basis for measuring.

In Fig. 2 we have, again, a tank *A* and a tube *C* containing water, and provided with a valve *c*. If the diameter of the tube is 13.5 inches, the sectional area would be very nearly 1 square foot, and a section of the tube 12 inches long would

contain 1 cubic foot. Let the divisions *b*, *b*, measured off along the tube, each represent 1 cubic foot. If the length of the tube is known, we are now able to say how many cubic feet it contains. It is also possible to say how many cubic feet pass the line *a a* in a given time, if the water is flowing and the velocity of flow is known. But let it be distinctly understood that, when we speak of the cubic foot as a unit, it is absolutely independent of the pressure in the tube, and it is immaterial whether the water is in motion or not.

7. Unit of Quantity.—The electrical unit of quantity is the *coulomb*. It signifies a certain quantity of electricity, either at rest, distributed on the surface of some substance, or in motion along a conductor. In this Paper the coulomb is used as the unit of quantity of electricity flowing along a conductor. In another Paper of the Course the unit of quantity of electricity at rest will be considered. In no case does it signify pressure or speed ; it represents quantity—nothing else.

Should we open the valve *c*, Fig. 2, and allow the water to flow out into a tank measuring 1 cubic foot, it would be possible to say how many cubic feet pass the valve in a given time. It would make no difference whether the rate of flow is so slow as to require a whole day or only 1 minute for the passage of 1 cubic foot of water.

Similarly, with an electric current, a certain quantity in coulombs may pass a given point, but the speed and the pressure have no direct part in the measurement of the quantity.

THE AMPERE.

8. Strength of Current.—The use of the coulomb, as a unit of quantity, would be rather limited, and we should soon find that a knowledge of the speed with which the current flows, that is to say, the number of coulombs that pass in a given time, would be of more practical use. The coulomb as a unit is not much used in therapeutics. If the speed be such that 1 coulomb passes per *second*, the rate of flow, or strength of current, is called *1 ampere*.

It is now clear that, if we divide the quantity in coulombs by the time in seconds, the quotient will give the strength in amperes; or, $\frac{\text{coulombs}}{\text{seconds}} = \text{amperes.}$

Or, let c = amperes; Q = coulombs; and t = seconds; then,

$$c = \frac{Q}{t}.$$

EXAMPLE.—If, in a conductor, 100 coulombs pass a certain point in 5 seconds, what is the current-strength in amperes?

SOLUTION.—Applying formula, $c = \frac{Q}{t}$, we get $\frac{100}{5} = 20$ amperes. Ans.

The current-strength is best ascertained by observing the ammeter; the current-pressure, by observing the voltmeter; and the resistance, by application of Ohm's law.

9. Pressure.—When water is flowing through a tube, it is subject to a certain resistance, depending on the length of the tube, its sectional area, and the condition of its interior surface.

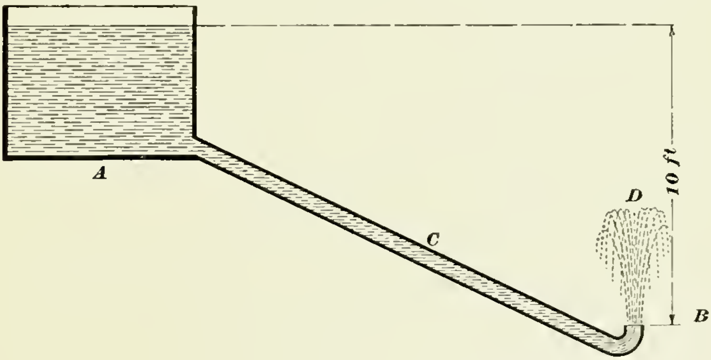

FIG. 3.

If the surface is rough or contains numerous projections, it will materially check the flow of the water.

When the level of the water in tank A, Fig. 3, is 10 feet above the surface B, the stream escaping from the lower end of the tube C should theoretically reach the same height. It does not do so, however, the top of the jet not reaching more than

one-half the height of *A*. The water, while passing through the tube, has met so much resistance that by the time it reaches the end it has lost one-half of its pressure. We can, by lowering the tank, reach a height where the pressure would be so small that the water would barely be able to flow out of the tube. The excess of pressure at the tank end is at this point consumed entirely in overcoming the resistance of the pipe *C*.

THE OHM.

10. Resistance.—Electricity is also subject to *resistance*, although of a different nature. The resistance offered to the flow of electricity has very much the same effect as the resistance offered to the flow of water. *A current cannot pass through any conductor without losing some of its pressure; the loss may in some cases be very large, in others so small that it is difficult to measure it.* The E. M. F. of an electric current is always reduced by the resistance of the conductor through which it flows. The resistance is determined by the substance of which the conductor is made (some substances offering more resistance than others), by its sectional area, and by its length.

11. Specific Resistance.—To facilitate comparisons and calculations, it has been found advisable to take a certain length and cross-section of the various substances used for conductors to determine the resistance, and to call this their *specific resistance*. The unit adopted for length is the inch, and for cross-sectional area the square inch; the specific resistance will therefore be the resistance of 1 cubic inch of the various substances taken at a temperature of 0° Celsius.

If we wish to measure the length of a rope, we need some unit in which to express its length, otherwise we would be limited to a comparison with other ropes of known lengths. Adopting the unit of 1 foot makes it easy to signify any length simply by stating the number of feet it contains.

Should we attempt to measure the various specific resistances without having a unit, we would be placed in a position similar

to that of measuring lengths without a unit. It would be possible to compare the various resistances, but a unit would be needed in which they could be all expressed, independently of one another. For this purpose the resistance of a column of mercury of a given length and sectional area has been chosen. The dimensions of the column expressed in inches are as follows: length, 41.7323 inches; sectional area, .00155 square inch. When this unit was established, the dimensions of the column were given in centimeters and square millimeters, the height being 106 centimeters and the sectional area 1 square millimeter. In each case the temperature of the column should be that of freezing water. This standard is called the *legal ohm*, or simply *ohm*. The specific resistance of metals is so small a fraction of an ohm that it often is found more convenient to employ as a unit the one-millionth part of an ohm, called a *microhm*.

The following table gives the specific resistances of the most important substances; also, their relative resistances as compared with that of silver.

Name of Metal.	Resistance of 1 Cubic Inch at 0°. Microhm.	Relative Resistance to Silver.
Silver, annealed	.5921	1.000
Copper, annealed	.6292	1.063
Silver, hard drawn	.6433	1.086
Copper, hard drawn	.6433	1.086
Gold, annealed	.8102	1.369
Gold, hard drawn	.8247	1.393
Aluminum, annealed	1.1470	1.935
Zinc, compressed	2.2150	3.741
Platinum, annealed	3.5650	6.022
Iron, annealed	3.8250	6.460
Nickel, annealed	4.9070	8.285
Tin, compressed	5.2020	8.784
Lead, compressed	7.7280	13.050
German silver	8.2400	13.920
Antimony, compressed	13.9800	23.600
Mercury	37.1500	62.730
Bismuth, compressed	51.6500	87.230

12. Variation of Resistance With Length.—It was stated in Art. **10** that the resistance of a conductor depends not only upon the material of which it is made, but also upon its length and cross-sectional area.

Referring to Fig. 3 it will be reasonable to suppose that, by doubling the length of the tube C, the resistance would also be doubled. The resistance of an electric conductor acts in the same manner; for example, *the resistance of a conductor is directly proportional to its length.* Thus, a copper wire 50 feet long would have twice the resistance of one 25 feet long.

To find the resistance of a conductor when the resistance of a certain length of the conductor is known:

Let r_1 = known resistance;
r_2 = resistance that it is desired to find;
L_1 = the length, the resistance of which is known;
L_2 = the length, the resistance of which is to be found.

Then, since the resistance of a conductor is directly proportional to the length, we have

$$r_1 : r_2 :: L_1 : L_2, \text{ or } r_2 = \frac{r_1 \times L_2}{L_1}.$$

NOTE.—The two lengths should always be reduced to the same unit.

EXAMPLE.—Find the resistance of 1 mile of copper wire, if the resistance of 10 feet of the same wire is .013 ohm.

SOLUTION.— $r_1 = .013$ ohm; $L_1 = 10$ feet; and $L_2 = 5{,}280$ feet. Therefore,

$$.013 : r_2 :: 10 : 5{,}280, \text{ or } r_2 = \frac{.013 \times 5{,}280}{10} = 6.864 \text{ ohms. Ans.}$$

EXAMPLE.—Find the resistance of 11 inches of a German-silver wire, the resistance of 100 feet of the same wire being 2.4 ohms.

SOLUTION.— $r_1 = 2.4$ ohms; $L_1 = 100 \times 12 = 1{,}200$ inches; $L_2 = 11$. Therefore, $2.4 : r_2 :: 1{,}200 : 11$, or $r_2 = \dfrac{2.4 \times 11}{1{,}200} = .022$ ohm. Ans.

13. Variation of Resistance of Cross-Sectional Area.—Having seen the effect the length of a conductor has on its resistance, let us see how its cross-sectional area influences its resistance. If a wire, of a given cross-sectional area, conducts, say, 4 amperes, it would be taken as a matter of course that another wire of the same length and area connected

with the same source of supply would also conduct 4 amperes; thus, both together would conduct 8 amperes. In other words, by increasing the number of wires, the current-strength in amperes would increase in the same proportion. Conversely, by increasing the cross-sectional area, the current remaining the same, the resistance would be reduced in proportion. It will therefore be seen that *the resistance of a given conductor diminishes as its sectional area increases; that is, the resistance varies inversely as the sectional area.*

To find the resistance of a conductor when its sectional area is varied and other conditions remain unchanged:

Let r_1 = original resistance;
r_2 = required resistance;
a_1 = original sectional area;
a_2 = changed sectional area.

Since the resistance varies inversely as the sectional area,

$$r_1 : r_2 :: a_2 : a_1, \text{ or } r_2 = \frac{r_1 a_1}{a_2}.$$

Example.—The resistance of a conductor, the sectional area of which is .025 square inch, is .32 ohm; what would be the resistance of the conductor if its sectional area were increased to .125 square inch, other conditions remaining unchanged?

Solution.— $r_1 = .32$ ohm; $a_1 = .025$ square inch; and $a_2 = .125$ square inch. Therefore,

$$.32 : r_2 :: .125 : .025;$$

or, $$r_2 = \frac{.32 \times .025}{.125} = .064 \text{ ohm. Ans.}$$

Example.—The sectional area of a conductor is .01 square inch, and its resistance is 1 ohm; if its sectional area is decreased to .001 square inch, and other conditions remain unchanged, what will be its resistance?

Solution.— $r_1 = 1$ ohm; $a_1 = .01$ square inch; and $a_2 = .001$ square inch. Therefore,

$$1 : r_2 :: .001 : .01;$$

or, $$r_2 = \frac{1 \times .01}{.001} = 10 \text{ ohms. Ans.}$$

Since the sectional area of a round conductor is proportional to the square of its diameter [sectional area = (diameter)^2 $\times$ .7854], it follows that the resistance of a round conductor is inversely proportional to the square of its diameter.

Let r_1 = original resistance;
r_2 = required resistance;
d_1 = original diameter;
d_2 = changed diameter.

Then, $r_1 : r_2 :: d_2^2 : d_1^2$, or $r_2 = \frac{r_1 d_1^2}{d_2^2}$.

EXAMPLE.—The resistance of a round copper wire .12 inch in diameter is .64 ohm; find the resistance of the conductor when its diameter is increased to .24 inch, the other conditions remaining unchanged.

SOLUTION.— r_1 = .64 ohm; d_1 = .12 inch; and d_2 = .24 inch. Therefore,

$$.64 : r_2 :: .24^2 : .12^2;$$

or, $$r_2 = \frac{.64 \times .12^2}{.24^2} = \frac{.64 \times .0144}{.0576} = .16 \text{ ohm. Ans.}$$

EXAMPLE.—The diameter of a round wire is .1 inch, and its resistance is 2 ohms; what would be its resistance if its diameter were decreased to .02 inch and the other conditions remain unchanged?

SOLUTION.— r_1 = 2 ohms; d_1 = .1 inch; and d_2 = .02 inch. Therefore,

$$2 : r_2 :: .02^2 : .1^2;$$

or, $$r_2 = \frac{2 \times .1^2}{.02^2} = \frac{2 \times .01}{.0004} = 50 \text{ ohms. Ans.}$$

14. Ohm's Law.—We have seen that the *volt* is the unit of pressure, the *ampere*, the unit of current-strength, and the *ohm* the unit of resistance. It will now be necessary to see how these units are related to one another; to see what effect the volt and the ohm have on the strength of a current of electricity; and to see how much pressure is lost when a current passes through a given resistance. These questions are of an eminently practical nature and of daily occurrence; it is therefore of great importance that we should be able to answer them correctly.

The law answering these questions was first stated by Dr. G. S. Ohm, and for this reason it is called *Ohm's law*.

In general, it is represented by the equation

$$\text{amperes} = \frac{\text{volts}}{\text{ohms}}, \text{ or } C = \frac{E}{R}. \qquad (a)$$

Transposing the factors, the law may also read

$$\text{ohms} = \frac{\text{volts}}{\text{amperes}}; \qquad (b)$$

or, $$\text{volts} = \text{amperes} \times \text{ohms}. \qquad (c)$$

Formula (*a*) determines the strength of current that will flow in a conductor of a given resistance, when the pressure in volts is known.

EXAMPLE.—A circuit has a resistance of 50 ohms and an available pressure of 100 volts; what is the strength of the current in amperes?

SOLUTION.—Applying formula (*a*) amperes $= \frac{\text{volts}}{\text{ohms}}$; hence,

$$\text{amperes} = \tfrac{100}{50} = 2. \quad \text{Ans.}$$

EXAMPLE.—If the pressure in a conductor is 3 volts and the resistance is 15 ohms, how many amperes will flow?

SOLUTION.—Amperes $= \frac{\text{volts}}{\text{ohms}} = \frac{3}{15} = \frac{1}{5}$ ampere. Ans.

NOTE.—The conditions may be such that the strength of a current is too great and that it is desirable to insert a resistance to reduce it. In that case formula (*b*) should be used.

EXAMPLE.—The E. M. F. of a circuit is 500 volts; it is desirable to have a current of .5 ampere flowing in it; what should be the resistance of the circuit?

SOLUTION.—According to formula (*b*), ohms $= \frac{\text{volts}}{\text{amperes}}$; hence,

$$\frac{500}{.5} = 1{,}000 \text{ ohms.} \quad \text{Ans.}$$

NOTE.—To find how much pressure it will require to force a current through a given resistance, it will be necessary to use formula (*c*).

EXAMPLE.—How much pressure will it take to force a current of 18 amperes through a resistance of 5 ohms?

SOLUTION.—Formula (*c*) states that volts = amperes × ohms; hence, $18 \times 5 = 90$ volts. Ans.

A definition of an ohm was given in Art. **11**, but, as we have now learned the use of Ohm's law, it may be well to give some additional information regarding the relation of the units to one another.

Referring to formula (*c*), we have volts = amperes × ohms. It follows from this that a *unit potential*, or *volt*, would be that electromotive force which would force a current of *1 ampere* through a resistance of *1 ohm*.

THE JOULE.

15. Unit of Work.—To set a current of water flowing, it is necessary to perform a certain amount of *work*. In Fig. 1 it was seen that the tank B would have to be raised to a certain height before the water would run, and it is easily seen that the position of the tank determines the pressure and strength of the current; that is to say, the greater the height, the greater the pressure. But to raise the tank requires an expenditure of work; that is, a given weight in pounds must be lifted through a distance of so many feet. In mechanics the amount of *work* done is determined by the distance through which the force acts. The *unit of work* is the *foot-pound;* it is the work done in lifting 1 pound through a vertical distance of 1 foot. Multiply the force in pounds by the distance in feet, and the product is the work, in foot-pounds. When we lift a weight of 200 pounds through a vertical distance of 2 feet, we perform 400 foot-pounds of work; should we lift 400 pounds only 1 foot high, the result is still 400 foot-pounds, as before. In fact, it is immaterial what relation the two factors have to each other, so long as their product equals 400.

In sending a current of electricity through a conductor, work is done in a similar manner. We have seen that the unit quantity of electricity is a coulomb; if a pressure of 1 volt forces a quantity of electricity of 1 coulomb through a conductor, one *unit of work* has been expended, and this unit is called a *joule*. 1 joule is equivalent to .7373 foot-pound, or 1 foot-pound is equal to 1.356 joules.

Therefore, to find the amount of electrical work performed in joules, it is necessary to multiply the quantity of electricity in coulombs that has passed in the circuit by the pressure in volts.

Let J = number of joules;
E = pressure in volts;
Q = number of coulombs.

Then,
$$J = Q \times E.$$

EXAMPLE.—Find the amount of work done in joules when 30 coulombs of electricity are being forced through a conductor with a pressure of 10 volts.

SOLUTION.— $J = Q \times E = 30 \times 10 = 300$ joules. Ans.

NOTE.—It was shown that an ampere means 1 coulomb per second; when, therefore, the current-strength in amperes, the time during which the current flows, and the pressure are given, it is possible, from these items, to calculate the work in joules.

EXAMPLE.—Find the amount of work performed in joules when a current of 15 amperes flows for ½ hour under a pressure of 30 volts.

SOLUTION.—Reducing the time to seconds gives $30 \times 60 = 1,800$ seconds; 15 amperes mean 15 coulombs per second; therefore, $15 \times 1,800 = 27,000$ coulombs, multiplied by 30 volts, gives 810,000 joules. Ans.

THE WATT.

16. Power.—It must be borne in mind that, when speaking of work performed, *time* does not enter as an element. This is important, as many confusing statements result from speaking of time in connection with work. No mention was made of time when we were speaking of foot-pounds, coulombs, or joules, and purposely so, in order to avoid confusion. It makes no difference whether it takes 1 year or 1 minute to perform a given amount of work; the work in either case is of the same magnitude. Neither does it make any difference whether the quantity of electricity in coulombs forced through a circuit by a certain number of volts requires 1 minute or 1 hour to pass. In either case the work performed is the same.

But when we speak of the *rate* of doing work, or *power*, that is an entirely different matter; a sharp distinction must be made between *work* and *power*. In daily life these terms are used with the understanding that they mean the same thing; force, even, is supposed to be identical with power. Let it, therefore, be repeated that if a force acts through a certain distance it performs *work*, and that *power* is the *rate* at which this work is performed.

For instance, a boy may be able to do a certain amount of *work* in pumping water out of a well. If time does not have to be considered, he may be able to serve the purpose; but if it is

necessary to get the water out in the shortest possible time, it is evident that a strong man is required. Why? Because he has more *power* at his disposal and is able to perform the work at a quicker rate. The rate at which two machines perform the same amount of work is proportional to the time expended. The unit of power in mechanics is *1 foot-pound per minute.*

17. Rule for Finding the Power.—The power of a machine may always be determined by *dividing the work it performs in foot-pounds by the time in minutes required to do the work.*

Let P = power in foot-pounds per minute;
F = force in pounds;
D = distance in feet;
T = time in minutes.

Then, $$P = \frac{F \times D}{T}.$$

EXAMPLE.—If a machine performs 10,000 foot-pounds of work in 10 minutes, what is its power in foot-pounds per minute?

SOLUTION.—Applying the equation for power, we have

$$P = \frac{F \times D}{T} = \frac{10{,}000}{10} = 1{,}000 \text{ ft.-lb. per min. Ans.}$$

18. Unit of Power.—We saw, in measuring work performed by electricity, that the joule was the unit used. When time has to be considered it is customary to use the *second* only. The unit of power used is therefore the *joule-per-second*, or the *watt*. As 1 joule is 1 coulomb × 1 volt, and as 1 watt is $\frac{1 \text{ coulomb}}{1 \text{ second}} \times 1$ volt, it follows that *1 watt* is *1 ampere × 1 volt*, since 1 ampere is 1 coulomb per second. Therefore, when 1 volt causes a current of 1 ampere to flow in a circuit, electrical work is performed at the rate of 1 *watt*.

Useful working formulas are as follows: 1 volt × 1 ampere = 1 watt, or the unit of electric power. 1 volt × 1 ampere × 1 second = 1 joule, or the unit of electric work.

19. Horsepower.—The units, *foot-pounds per minute* and *watts*, are too small when large machines are under consideration.

A larger unit is therefore desirable, and for this purpose 33,000 foot-pounds per minute has been chosen and called *1 horsepower*, that being the power a strong horse is able to develop for a short time. It requires 746 watts to make 1 horsepower; that is, 746 watts is equal to 33,000 foot-pounds per minute.

Rule.—*To express the rate of doing electrical work in horsepower units, find the number of watts and divide the result by 746.*

Let W = power in watts;
H. P. = the horsepower.

Then,
$$\text{H. P.} = \frac{W}{746}.$$

EXAMPLE.—When a pressure of 50 volts causes a current of 30 amperes to pass through a circuit, (*a*) how much power is required in watts? (*b*) how much in horsepower?

SOLUTION.—Since the power in watts is the product of the volts and amperes, we have $50 \times 30 = 1{,}500$ watts. From the formula $\text{H. P.} = \frac{W}{746}$, we get $\frac{1{,}500}{746} = 2.01$ H. P. Ans.

20. Unit Abbreviations.—When using Ohm's law, it is customary, for the sake of convenience, to use the terms volts, ohms, and amperes in an abbreviated form; thus, volts, pressure, or electromotive force are represented by the letter E; ohms, or resistance, by the letter R; and amperes, current-strength, or current-volume, by C. In the following pages Ohm's law will be represented by these letters, and in its three variations will appear as

$$C = \frac{E}{R}; \; R = \frac{E}{C}; \text{ and } E = R \times C.$$

Power in watts will be $W = E \times C$; but can also be expressed by the two following equations, viz.:

$$W = C^2 \times R; \text{ or } W = \frac{E^2}{R}.$$

EXAMPLE.—If a current of 50 amperes is forced through a resistance of 40 ohms, what power is expended?

SOLUTION.—Applying the formula $W = C^2 \times R$, we have
$W = 50 \times 50 \times 40 = 100{,}000$ watts, or 134.05 horsepower. Ans.

EXAMPLE.—If 3,000 volts pressure is supplied to a circuit of 6 ohms resistance, what power is needed in horsepower?

SOLUTION.—From the formula $W = \frac{E^2}{R}$, we have

$$W = \frac{3,000 \times 3,000}{6} = \frac{9,000,000}{6}$$

Dividing by 746 to reduce to horsepower, we have

$$\frac{9,000,000}{6 \times 746} = 2,011 \text{ horsepower, nearly. Ans.}$$

PRODUCTION OF ELECTROMOTIVE FORCE.

21. Devices for Creating E. M. F.—We have seen in the previous pages that certain conditions have to be fulfilled before a current of electricity is established. We know that it needs the creation of an E. M. F., a conductor to transfer the electricity from one place to another, and further, that this conductor must be of a certain material and cross-sectional area to fulfil its purpose in a satisfactory manner. It will now be necessary to describe the means for producing an E. M. F.

There are various devices for creating E. M. F., but all of them are not of the same importance. Some are rarely used for electrical purposes, and never in therapeutics. It will not be necessary, therefore, to describe them in these pages, and they will be mentioned only as possible sources. Their classification may be as follows:

1. Those producing an E. M. F. by means of chemical action, such as voltaic, or primary, or galvanic cells and secondary cells.

2. Those producing an E. M. F. by means of mechanical energy; for instance, dynamo-electric machines and electrostatic induction-machines, and faradic apparatus.

3. Those utilizing radiant energy, as light and heat, for the production of an E. M. F.; as, for example, the thermoelectric cell.

4. Animals and plants. Instances of animals are the torpedo and gymnotus. The roots and interior parts of trees are found to be negatively, and flowers, smaller branches, and fruits to be positively, electrified.

The first two classes only need be considered, and as the second cannot be understood until after the subject of electromagnetism has been studied, we will at present limit our discussion to the first class alone.

PRIMARY AND SECONDARY CELLS.

PRIMARY CELLS.

22. Direct Currents.—It is proved that, when two dissimilar substances are placed in contact, one of them always assumes the positive and the other the negative condition. This can be proved by the gold-leaved electroscope. There will therefore be a difference of potential between them. The amount of this difference may be small and difficult to measure, but a difference of potential will always be there. *If these effects are produced while any two substances make contact with each other in air, then the phenomenon properly belongs to the subject of static electricity, and will be treated in that division.* When the contact is made between metals in water or other fluids, the results are different and come under the class where an E. M. F. is produced by chemical action.

Placing a piece of copper and zinc in contact will develop a difference of electric potential which can easily be detected. The same result will follow if the plates are slightly separated from each other, and placed in a vessel containing saline or acidulated water, leaving a small portion of one end of the plates exposed. The exposed ends of the zinc and copper are now electrified to different degrees, or, in other words, there is a difference of electric *potential* between the plates; one plate being at a higher potential than the other.

When the exposed ends are connected together by a wire of any conducting material, the potential difference between the plates tends to equalize, and a momentary rush or discharge of electricity passes between the exposed ends through the conducting material, and between the submerged ends through the liquid. During its passage through the liquid, the electricity causes certain chemical changes to take place; these chemical

reactions in their turn cause a new difference of potential between the plates, which is followed immediately by another equalizing discharge, and that by a further difference of potential, and so on. These changes follow one another with great rapidity; so rapidly, in fact, that it is impossible to distinguish them, and they appear absolutely *continuous*. The equalizing flow that is constantly taking place from one plate to the other is known as a *direct current* of electricity, which may or may not be continuous. Consequently, a *direct current becomes continuous when the difference of potential is constantly maintained*, and when no mechanical device is employed to interrupt it.

We will see later on that the E. M. F produced by other means is not constant, and that, therefore, the equalizing flow which results, though continuous, is not of a constant strength. It may approximate very closely to it, yet the voltaic current stands as the main representative of an absolutely direct current.

23. Simple Voltaic Cell.—A simple voltaic, or galvanic, cell is shown in Fig. 4. It consists, essentially, of a vessel *A*, containing saline or acidulated water, in which are submerged two plates of dissimilar metals *C* and *Z*, or one metal and a metalloid.

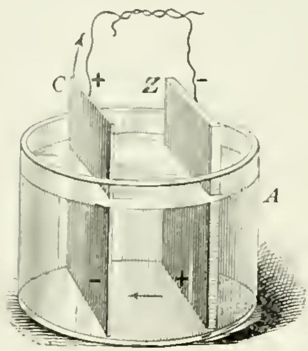

FIG. 4.

The two dissimilar metals, when spoken of separately, are called *voltaic elements;* when taken collectively they are known as a *voltaic couple.*

An *electrolyte* is a compound chemical substance in solution, which undergoes decomposition when traversed by an electric current.

A *voltaic battery* is a number of simple voltaic cells properly joined together.

The *terminals* of a cell are the parts of the plates outside of the electrolyte.

It should be remembered that the polarity of that end of the

plate or voltaic element which is acted upon by the electrolyte is always of opposite sign to its terminal. For instance, in the case of the zinc-and-copper couple, the terminal of the zinc plate, or that part outside of the electrolyte, would be spoken of as the *negative* terminal, while that part of the copper plate outside of the electrolyte would be spoken of as the *positive* terminal. When mention is made of the positive or negative pole of a cell, reference is always made to the *exposed* parts of the elements, and no attention is paid to the submerged parts. The symbols + and − refer to the parts of the elements not contained in the electrolyte, and are always of an opposite sign to the parts submerged in the electrolyte.

24. Chemical Actions Occurring in a Simple Cell. When a piece of ordinary zinc is placed alone in dilute sulfuric acid, one to twenty, the zinc is attacked by the acid and a part of it is dissolved into a salt of that metal called *sulfate of zinc*. At the same time, the electrolyte is decomposed and *hydrogen gas* is liberated from it, coming up from around the zinc in small bubbles, and the whole mass of the liquid becomes heated. If the zinc is absolutely pure, the chemical actions take place more slowly; the bubbles of hydrogen do not immediately rise to the surface, but form around the zinc, protecting it from further action of the acid. When a plate of commercial zinc is immersed in dilute sulfuric acid, we have in reality a voltaic cell. This will be readily understood by referring to the E. M. F. series, and by a knowledge of the impurities of zinc. By placing another metal in the water, say a piece of copper, and connecting its exposed end with that of the zinc by means of a conductor, the chemical action becomes exceedingly vigorous again. Large quantities of hydrogen gas are liberated, but, instead of the bubbles appearing around the zinc, they form around the copper and come to the surface at that point. The energy that in the former case was expended in heating the liquid, now appears in the form of electric energy. Whenever the connection between the exposed ends is broken, all chemical action ceases and the cell remains inactive until the two metals are again connected. This refers to absolutely pure zinc.

Then the chemical action will again begin and continue for some time, the duration of the action depending on the condition of the electrolyte. It is found that the amount of electricity set free will depend on the quantity of zinc dissolved by the acid; the latter quantity will also determine the quantity of hydrogen gas developed. It is clear that after a time the solution will have changed into one of sulfate of zinc, and will be unable to dissolve the zinc any further. Then the action of the cell will cease, and the acid will have to be renewed before more current will flow. Whether the zinc must be renewed or not depends on the amount of zinc remaining; if there is enough to suffice for a second charge, the same zinc will answer.

25. Local Action.—It must be remembered that a current will be established between the elements of a voltaic cell only when they are in direct contact or connected by means of an outside conductor. We saw that wherever a difference of potential exists there is a tendency to equalization by a flow of electricity from the higher potential to the lower. It follows from this that after a time the potential of both elements would be the same and no current would flow; but, fortunately, chemical action sets in as soon as the potential difference is lowered, and immediately brings it up to its initial value. We should suppose from this that on disconnecting the exterior conductor, that is, on opening the circuit, all chemical action would cease, because no tendency existed to lower the potential difference. Such would be the case if the zinc were perfectly pure, but, as commercial zinc is ordinarily mixed with particles of iron, arsenic, and other metals, the conditions are altered. By consulting the electromotive series, Art. **27**, it is observed that iron is half way between zinc and copper, and that a difference of potential will be produced between them which, though not as high as in the former case, will be sufficient to start a current. In other words, there will be a *local action;* that is to say, currents flow between various places on the same plate. As these currents do not manifest themselves outside the cell, they will evidently waste the zinc to no purpose, both when the circuit is open and when it is closed. This explains why the

zinc plate in Fig. 4 is attacked by the acid in the absence of the copper plate. There is then a local action all over the plate, caused by the various impurities existing in the zinc.

26. Amalgamation.—To prevent this local action, the zinc is submitted to a process called *amalgamation*. By this means the iron is separated from the zinc and made harmless. Before amalgamating the zinc it is first dipped into an acid bath, which removes all impurities from the surface; then a little mercury is poured over it and rubbed into the surface with a rag or a piece of galvanized iron. When finished, the surface should be as bright as silver. Another way to amalgamate the zinc is to immerse it in an acid solution of mercuric nitrate. The zinc unites with the mercury, and the result, by either method, is that the whole surface is covered with a pasty amalgam. The iron does not participate in this combination, but remains undissolved and appears on the surface of the amalgam as small particles, and, as soon as the cell begins its action, they are carried away by the hydrogen bubbles. It is a peculiarity of this amalgam that it does not leave the zinc when the latter dissolves, but immediately attaches itself to fresh portions of the same. The surface will therefore always appear bright and clean. If a hissing noise is heard when the zinc is placed in the electrolyte, it signifies that the zinc requires reamalgamation.

27. Electromotive Series.—In any voltaic cell, the element which is acted upon by the electrolyte will always be the generating-plate, and its electrode is always negative.

The following list of voltaic elements compose the *electromotive series:*

CONTACT IN AIR.

+ Zinc	Antimony
Cadmium	Copper
Tin	Silver
Hydrogen	Gold
Lead	Platinum
Iron	Carbon
Nickel	— Oxygen
Bismuth	

Any metal in this list is electropositive to every other below it, and electronegative to every other above it.

Any two of these metals form a voltaic couple, and produce a difference of potential when submerged in saline or acidulated water, the one standing first on the list being the generating-plate, and the other the collecting-plate. For example, if nickel and carbon are used, the nickel will be acted upon by the liquid and will form the generating-plate; but if nickel and zinc are used, the zinc will be acted upon by the liquid and will form the generating-plate.

The farther apart the elements stand in the above list, the greater will be their difference of potential. For example, the difference of potential developed between zinc and carbon is much greater than that developed between zinc and nickel; in fact, the difference of potential developed between zinc and carbon is equal to the difference of potential developed between zinc and nickel plus that developed between nickel and carbon.

This may be summed up in the following law, as first stated by Volta: *The difference of potential developed between any of these metals is equal to the sum of the difference of potentials of all those intervening.*

In the simple cell illustrated in Fig. 4, we have seen that zinc was the element acted upon by the electrolyte, and that this element is called the generating-plate. Strictly speaking, the surface of contact between the liquid and the metal is the place of action, and would more properly be called the generating-plate.

The other element—in this instance, copper—is called the collecting-plate, and serves merely as a means of connecting the external circuit to the electrolyte. In some cells the chemical action takes place between two different liquids, in which case whatever solid conducting bodies are used act merely as connectors or terminals.

In therapeutics, the term *anode* is used simply to indicate the positive terminal, and *cathode* to indicate the negative terminal.

28. Polarization and Depolarization.—When communication was established between the copper and the zinc

elements in the cell under consideration, it was observed that large quantities of hydrogen bubbles collected around the copper. If at or near the latter there should be placed some substance with which the nascent hydrogen could unite, the energy liberated by the reaction would increase the E. M. F. of the cell. But as, in the present case, there is no such substance at hand, the bubbles remain undisturbed and increase in number, and the consequence is that the action of the cell decreases materially, even after the lapse of a few seconds. The resistance and the counter E. M. F. of the hydrogen is the cause of this. Hydrogen is a poor conductor of electricity, and the layer of gas which it forms on the collecting-plate increases the resistance of the cell. In addition to this comes the tendency of the hydrogen to set up an E. M. F. in opposition to the existing current, as it was seen in Art. 27 that there is much less difference between zinc and hydrogen than between zinc and copper; that is to say, the copper element tends to become generating instead of collecting. The restraining action of these opposing factors may eventually reach such a value as to stop the action of the cell entirely. When the cell is in this condition it is said to be *polarized*. It need hardly be said that it is of the utmost importance to remove the hydrogen, either by mechanical or chemical means. Any agent used for this purpose is called a *depolarizer*.

29. Depolarization of Cells.—Various mechanical devices for depolarizing cells have been used; the collecting-plate has been arranged to be agitated in the liquid, or to be entirely removed from the liquid at intervals; and the collecting-plate, or in some instances both plates, have been made in the form of disks, dipping for about half their diameter into the electrolyte. On rotating the disks, the hydrogen is prevented from forming on the collecting-plate by its motion. Again, the liquid itself may be kept in constant circulation by various means. Sometimes the surface of the collecting-plate is roughened, and provided with small projections on which the gas collects more freely and with more facility for detaching itself, and in the form of bubbles to rise to the surface. But, as none of these devices prevent

depolarization altogether, they are commercially of little value, especially as chemical depolarizers are much more convenient.

30. Chemical Depolarization.—Depolarization by *chemical* means may be accomplished by surrounding the collecting-plate with a solid or liquid with which the nascent hydrogen may combine. This combination usually disposes of the gas, and prevents the bad effects due to its deposit on the collecting-plate. Under these circumstances, the compound formed at the collecting-plate is usually water, the depolarizer being generally a substance rich in oxygen, with which the hydrogen combines. This water has the effect of diluting the electrolyte already weakened by the combination with the generating-plate; but, by properly selecting the depolarizer with reference to the electrolyte, the chemical combination at the collecting-plate may be such that it will, either directly or by further combination, replace that part of the electrolyte which has been combined with the generating-plate. By this means the electrolyte will be kept at the same strength and composition throughout the life of the generating-plate or of the depolarizer.

31. Rate of Depolarization.—The *rate* at which any depolarizer will perform its function depends upon many conditions. *No depolarizer will keep the E. M. F. of a cell constant for all currents;* for, after a certain limiting current has been reached—the limit depending upon the sizes of the various parts of the cell—the formation of the free element of the electrolyte is more rapid than its absorption by or recombination with the depolarizer, and the surplus gas will then collect on the collecting-plate.

In the case of depolarizers that, by the formation of water, dilute the electrolyte, the E. M. F. is reduced by continued use of the cell, even if the current output be small. These facts should be remembered in dealing with the various depolarizers.

32. Primary Batteries as Sources of Electrical Energy.—Primary batteries, as sources of electrical energy, are used principally in those cases where the use of the current is intermittent, such as for ringing bells, for lighting gas, etc., or where a small but steady current is required for long periods of

time, as in electrotherapeutics, in telegraphy, in telephony, for laboratory and for testing purposes. Their general use on a large scale as sources of electrical energy for lighting or for power purposes is precluded, at least at present, by the comparatively great cost of the material consumed, and the expense of insulation and maintenance.

For example, the bichromate battery is about the cheapest in point of cost of materials consumed, and in this the materials alone would cost about 28 cents per horsepower per hour when used on a large scale. When the electrical energy is produced by means of dynamos, the cost per horsepower per hour is ordinarily about 5 or 6 cents, and in many cases much less. The cost of material in the silver-chlorid battery is about $1.35 per horsepower per hour.

This high cost of the power does not, however, prevent batteries from being largely used for the purposes previously outlined, and their practical application is an important part of electrical engineering.

CELLS.

33. Classification.—The various kinds of voltaic cells may be divided into classes as follows:

1. *Cells in Which There is No Depolarizer.*—These are the simplest form of cells, but, because they polarize rapidly, cells of this class, commonly called *open-circuit* cells, are used only for intermittent work.

2. *Cells With a Depolarizing Electrolyte.*—In this class of cells the electrolyte is of such a nature that either no hydrogen is formed or the liquid contains a substance with which the hydrogen unites. As this action takes place mainly at the collecting-plate, there is little distinction, so far as action goes, between this latter type of Class 2 and the following class.

3. *Cells With a Liquid Depolarizer.*—In this class of cells the collecting-plate is surrounded by a depolarizing liquid which is, by mechanical means, prevented from mixing with the electrolyte. The method that is usually employed is to separate the two liquids by a porous partition, which allows of their electrical

contact without mechanical mixture, if their respective specific gravities are nearly the same. If the latter differ materially, gravity will keep the two liquids apart, one being above the other in the containing vessel.

4. *Cells With a Solid Depolarizer—Dry Cells.*—In many respects, this class is identical in action with Class 3, the only difference being that the depolarizer is a solid instead of a liquid. If the solid depolarizer is granular, or in the form of powder, it is often necessary to employ a porous partition between the collecting-plate surrounded by the depolarizer and the electrolyte. This is merely to keep the depolarizer in place, and may be dispensed with if the depolarizer is in the form of a paste or solid body fastened upon the collecting-plate. In fact, the depolarizer itself frequently forms the collecting-plate when it is a solid conducting material, the office of the collecting-plate being primarily to establish a connection between the electrolyte and the external circuit.

Ordinarily, cells are classed as "single-fluid" and "two-fluid" cells; but, as such a classification has little reference to this principle of operation, it will not be used in this Paper. All the different kinds of cells will not be described in these pages, and reference will only be made to those that have shown themselves most suitable for the purpose of electrotherapeutics.

CELLS WITH NO DEPOLARIZER.

34. The Volta Type.—In this class are included cells of the *Volta* type, illustrated in Fig. 4. In place of copper as a collecting-plate, many other elements have been used, notably in the Smee cell, using platinum or platinized silver, and cells of various other makes, in which the collecting-plate is of iron. The available E. M. F. of the Smee cell is hardly more than .5 volt.

It was found that copper could be advantageously replaced by porous carbon. The E. M. F. of the porous-carbon cell is about 1.35 volts. To prevent the electrolyte from being too quickly exhausted, there is sometimes placed in the cell a

porous cup filled with strong sulfuric acid. As the dilute acid outside the porous cup becomes weaker, the stronger acid oozes through the sides of the porous cup and maintains the strength of the electrolyte.

In all the cells of this type the carbon is made as porous as possible, and of such shape that the surface exposed to the liquid is very large compared with the surface of the zinc. Thus the average area of the internal circuit of the cell is made large, and at the same time advantage is taken of the slight depolarization that occurs with a porous carbon of large surface. Porous carbon absorbs oxygen from the air, and some of the evolved hydrogen combines with this, thereby diminishing the tendency to polarization.

CELLS WITH A DEPOLARIZING ELECTROLYTE.

35. Bichromate Cells.—The best known cells of this type are the bichromate cells. Twenty of these cells form the best portable battery having a liquid electrolyte. These consist of a zinc-carbon couple, with an electrolyte composed of a solution of dilute sulfuric acid, mixed with a proportion of the *bichromate salts* of some metal, usually potassium. The purpose of the bichromate salt is to act as a depolarizer, which it does very satisfactorily, on account of the large quantity of oxygen that it contains. When, therefore, the hydrogen is liberated by the decomposition of the electrolyte, it unites immediately with the bichromate salt, forming water and a new salt known as *chrome alum*, which forms in crystals of a purplish color. If the salt of sodium is used instead of the salt of potassium, there is no formation of *chrome alum*, and the working capacity of the cell is therefore greater. The result of this combination is a high E. M. F. of about 2 volts. By the action of the acid in the electrolyte on the bichromate of potassium, chromic acid is formed. It has been proved that pure zinc is 175 times more soluble in acid containing a little chromic acid than in pure dilute acid. The zinc will be attacked by the acid whether any current is flowing or not—hence the importance of arranging

the zinc in such a manner that it may be lifted from the liquid when not in use.

36. The Grenet Cell.—A familiar type of bichromate cell is the *Grenet cell*, shown in Fig. 5. It consists of a bottle-shaped jar with a hard-rubber or porcelain cover from which two flat carbon plates C, C are suspended, parallel to and a short distance from each other. Between them hangs a zinc plate Z, supported by a sliding rod R, which may be drawn up until the zinc is entirely out of the liquid. The rod is held in any position by the thumbscrew T. On top of the brass rod is a binding-post B_1, the other terminal of the cell being the binding-post B connected to the two carbon plates C, C. The electrolyte is composed of 3 parts of potassium bichromate dissolved in 18 parts of water, to which is added 4 parts of sulfuric acid. The E. M. F. of the cell is 1.92 to 2 volts.

Fig. 5

37. Plunge-Batteries.—Cells of the bichromate type are often united to form what is called a *plunge-battery*. These are usually built with several cells, the various elements being connected in series to give an E. M. F. of 6 to 10 or more volts. All the elements are simultaneously raised out of or lowered into the liquid by a lever or windlass arrangement, as shown in Fig. 6, which represents a battery of five cells, all alike. The elements are zinc and carbon, there being three plates of zinc Z, and four of carbon C, in each cell. All the plates are suspended from a wooden cross-bar, which is supported by means of the chains H, H from the rod R. By turning the crank K on the rod, the plates may be raised or lowered into the jars J. Each cell is provided with two binding-posts B, B_1, connected, respectively, with the carbon and zinc plates. The cells may therefore be arranged in various combinations.

To this class belongs also the *Pabst* cell, in which wrought

iron and carbon are used as elements, and a solution of ferric chlorid as the electrolyte. The ferric chlorid is decomposed into ferrous chlorid and free chlorin, the latter uniting with

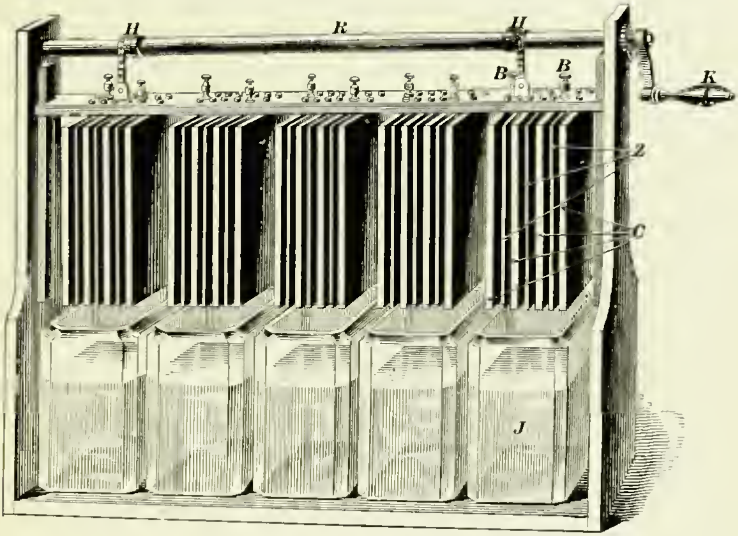

Fig 6.

the iron element. There is no polarization, as the liquid regenerates itself by absorbing oxygen from the air. It is very constant, but of low E. M. F., about .78 volt.

CELLS WITH A LIQUID DEPOLARIZER.

38. Nitric Acid as a Depolarizer.—Nitric acid (HNO_3), being rich in oxygen, is largely used as a depolarizing liquid in this class of cells. Its use is objectionable from the fact that, when deprived of a part of its oxygen, it gives off a gas, nitric oxid, which, on combining with the oxygen of air, becomes nitrogen peroxid, a disagreeable and even dangerous corrosive gas; consequently, the best of ventilation is essential where cells with this depolarizer are used.

39. Grove and Bunsen Cells.—The principal cells using this depolarizer are the *Grove* and the *Bunsen* cells, and some of

their derivatives. In the Grove cell the positive element is zinc; the negative, platinum. The platinum element is placed inside a porous cup and surrounded with nitric acid diluted with water. The E. M. F. of the Grove cell is 1.9 volts at ordinary temperatures. The Grove cell is a very old type, and has been made in many forms. The expense of the platinum element led to the adoption of the Bunsen cell, in which carbon is substituted for platinum. By using commercial nitric acid, specific gravity about 1.33, the E. M. F may be increased to 1.96 volts. About .35 volt is due to the action of the depolarizer. These cells are objectionable because of their odor, and must be situated in a place where this is not objectionable. They are useful for charging small accumulators.

40. Electropoion Fluid.—Another important type of this class of cell is the *bichromate* cell, in which the bichromate solution is not mixed with the electrolyte, but separated from it by a porous partition, with the effect that the zinc is not seriously attacked on open circuit. As to the E. M. F., chemical action, etc., this type is not sensibly different from the bichromate cell described above. The bichromate solution is usually, with the collecting-plate, placed in the outer vessel, the zinc and exciting liquid being inside the porous cup. The exciting liquid is usually dilute sulfuric acid having a Sp. Gr. of about 1.10. The depolarizing liquid is ordinarily of the composition given in Art. **36.** Under the name *electropoion fluid*, a bichromate mixture is prepared by dealers (all parts by weight) as follows: sulfuric acid, 2 parts, is mixed with water, 4 parts; in another vessel, 1 part of potassium bichromate is dissolved in three parts of boiling water, and, while hot, is mixed with the liquid first prepared. This liquid, when cold and more or less diluted, is suitable for use in most bichromate cells.

Bichromate cells are often constructed in which the liquids employed have such a difference in their specific gravities that they may be placed one above the other in the cell, no porous partition being required to keep them from mixing.

41. The Partz Cell.—The *Partz* cell, one form of which is illustrated in Fig. 7, is an example. This cell is a bichromate cell in which a solution of sodium chlorid or magnesium sulfate constitutes the electrolyte and surrounds the zinc Z; a bichromate solution, which acts as a depolarizer, surrounds the carbon plate C. The depolarizer, having a higher specific gravity than the electrolyte, remains at the bottom of the jar, and the two liquids are thus kept separate. To keep up the strength of the depolarizer, a glass tube T is suspended in the cell, having a small opening below the normal level of the bichromate solution. This tube is filled from time to time with crystals of what the manufacturers call *sulfochromic salt*, which is formed by the action of sulfuric acid on some bichromate solution, and when dissolved in water gives the same results as the electropoion fluid. The depolarizer, as it becomes weakened by use, is replenished by crystals in the tube T.

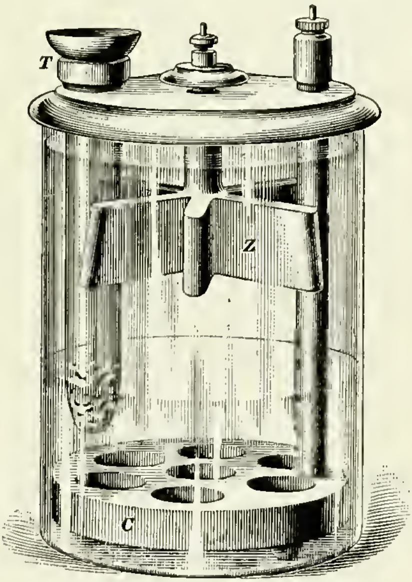

Fig. 7.

With the cell shown, which employs a $6'' \times 8''$ jar, the internal resistance is about 1 ohm with a solution of magnesium sulfate, and about .5 ohm with a solution of sodium chlorid, the E. M. F being the same, 1.9 to 2 volts, in either case. This cell is useful for either open- or closed-circuit work, as the depolarization is very complete; at the same time the local action on open circuit is almost imperceptible. The chrome-alum solution that forms, being heavier than the bichromate solution, descends to the lower part of the cell, so that the crystals form beneath the carbon plate, which is slightly raised

from the bottom of the jar; consequently, the formation of these crystals does not appreciably increase the internal resistance of the cell.

42. The Daniell Cell.—Another cell belonging to this class is the *Daniell*, a variation of which is illustrated in Fig. 8; it is here shown in the familiar form known as the *gravity*, or *crowfoot*, cell. The zinc Z, from the shape of which the cell has received its name, hangs from the edge of the glass jar; the copper C is connected to the external circuit by the wire W, covered with an insulating material on those parts submerged in the liquid. When the cell is set up, the copper plate is surrounded with crystals of cupric sulfate, until it is completely covered. The standard form of this cell is of the following dimensions: The jar is 6 inches in diameter, and is 8 inches high. The copper, made from three pieces of thin sheet copper 2 inches wide and 6 inches long, is riveted together in the middle; the outside pieces are then spread out, giving the copper the shape of a six-pointed star. A piece of No. 16 insulated copper wire is riveted to the middle strip. The zinc is in the shape shown, and weighs 3 pounds. About 2 pounds of cupric-sulfate crystals are required to charge the cell. The average internal resistance of a gravity cell of this size is about .5 ohm, and its E. M. F. is the same as the other forms of Daniell cell, 1.07 volts.

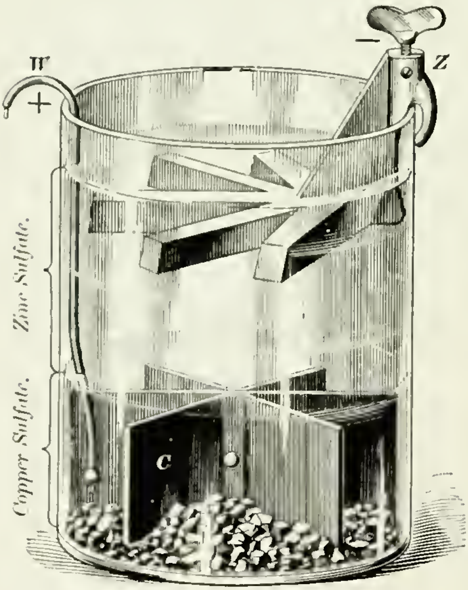

FIG. 8.

The maintenance of this type of cell is simple, it being necessary to renew the supply of cupric-sulfate crystals only when the solution becomes weak, which fact is indicated by the fall of the blue-colored liquid below the top of the copper plate. In addition to this, the density of the zinc-sulfate solution should be occasionally measured with a hydrometer, and if too dense (above 1.15 Sp. Gr.) a portion should be removed and replaced by water.

43. The D'Infreville Zinc.—To avoid waste, various forms of the zinc element have been suggested in place of the crowfoot pattern; one form, in which there is no waste whatever, is the *D'Infreville* wasteless zinc. This zinc is cast with a conical lug *C* on top (see Fig. 9) and a corresponding cavity in the under side of the zinc. When the zinc is nearly consumed, it is removed from its support, and the lug *C* inserted in the cavity of a new zinc, which is then placed in its support. The old zinc is thus placed underneath and is entirely consumed. The figure shows a cross-section of this form of zinc, the new zinc *A* resting on a partly consumed zinc *B* with the stub of a third zinc *C* beneath. The use of the Daniell cell in medical practice is limited chiefly to the charging of accumulators.

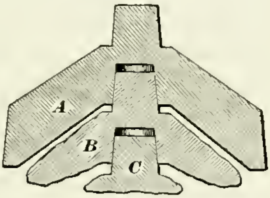

FIG. 9.

CELLS WITH A SOLID DEPOLARIZER.

44. The depolarizers that are used in this class of cells are generally substances containing a large proportion of oxygen, with which the nascent hydrogen unites, forming water. Solid depolarizers, like liquid depolarizers, are chosen on account of the large quantity of oxygen that they contain. The balance of the depolarizer is sometimes dissolved in this water, but it more often remains at the collecting-plate in the form of a solid, the water serving merely to dilute the electrolyte. In case the depolarizer is dissolved, the solution formed usually tends to keep up the strength of the electrolyte.

Among the most widely used depolarizers are the oxids of manganese, of copper, and of lead, and the chlorids of some

of the metals. The several sulfates of mercury, on account of the large quantities of oxygen which they contain, are also used for this purpose.

45. The Leclanché Cell.—The *Leclanché* cell is the best known and the most widely used cell of this type. It is used more by physicians than all other cells taken collectively. Its positive element is zinc, usually in the form of a rod; the electrolyte is a saturated solution of ammonium chlorid (sal ammoniac), and the negative element is carbon, surrounded by manganic oxid (peroxid of manganese), which is the depolarizer. The oxid is in the form of a coarse powder, and is usually contained in a porous cup, which allows free access of the electrolyte to the depolarizer and the negative element. Fragments of crushed coke (or carbon in other forms) are often mixed with the manganic oxid to decrease the resistance of the contents of the cup.

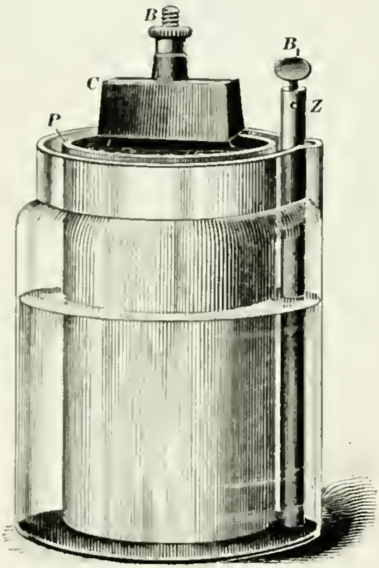

FIG. 10.

Fig. 10 shows the usual form of this type of cell. The porous cup P contains the manganic oxid and the carbon element, which projects from the top of the cup, a binding-post B being attached as shown. The glass jar is circular with a contracted top, in which a slight recess is formed for the zinc Z. The top of the zinc is provided with a binding-screw B_1, which serves as the negative terminal of the cell, B being the positive terminal. The top of the jar is coated with paraffin to prevent the crystals of sal ammoniac from "creeping" over the top of the jar as the liquid evaporates.

46. The cell illustrated in Fig. 10 has the following dimensions :

Jar	$4\frac{1}{2}''$ diameter, $6''$ high.
Zinc	$\frac{3}{8}''$ diameter, $6\frac{1}{2}''$ high.
Porous cup	$3''$ diameter, $5\frac{1}{2}''$ high.
Carbon	about $6'' \times 1\frac{3}{4}'' \times \frac{5}{16}''$

The weight of the zinc rod is about 3 ounces, and two-thirds of it is usually below the level of the liquid. There are 16 ounces of peroxid in the porous cup, and it requires nearly 4 ounces of ammonium chlorid to make sufficient solution for this size of cell. For each ounce of zinc consumed in the cell, 2 ounces of manganic oxid and 2 ounces of ammonium chlorid must also be consumed ; so, from the amount of these materials contained in the cell, it follows that there is enough peroxid in the porous cup to last while five or six zincs are being consumed, while the ammonium chlorid will not last longer than one zinc, as the zincs are usually replaced when eaten away to about $\frac{1}{8}$ or $\frac{1}{16}$ inch diameter. The consumption of zinc in the Leclanché cell is about 23 ampere-hours per ounce of zinc, and as about $1\frac{3}{4}$ to 2 ounces of each zinc rod may be consumed, the life of each zinc is then about 40 to 45 ampere-hours. The E. M. F. of this type of cell is about 1.48 volts, and its internal resistance about 4 ohms.

It is usual to seal the carbon and depolarizer into the porous cup by some compound such as sealing-wax, leaving small tubes or holes through which whatever gas not absorbed by the depolarizer may escape. This sealing necessitates the entire renewal of the porous cup with contents, when the depolarizer is exhausted ; to obviate this expense, some makers use a carbon porous cup and place the zinc inside, at the center, the space between the zinc and carbon being filled with peroxid. To this class belong also the *Samson* cell, and the *Hayden* cell.

47. Gonda-Leclanché Cell.—Another widely used form of Leclanché cell is the *Gonda-Leclanché*, which uses no porous cup whatever ; the manganic oxid is mixed with granulated carbon and some gummy substance, and compressed into cakes

under great pressure. These cakes are attached to the sides of the carbon plate and act in the same manner as the depolarizer in the regular form. Other modifications have also been made to avoid evaporation of the liquid.

48. Lalande-Chaperon Cell.—To this class also belongs the *Lalande-Chaperon* cell, which uses iron or copper surrounded with a layer of cupric oxid, which acts as a depolarizer, as the negative element. The positive element is zinc and the electrolyte a solution of caustic potash.

49. Edison-Lalande Cell.—The *Edison-Lalande* cell is a modification of the Lalande-Chaperon. The cupric oxid is molded under pressure into plates of the requisite size, being first mixed with magnesium chlorid, which, when the molded plates are heated, serves to bind the mass together. These plates are held in copper frames enclosing the edges of the plates. The positive element in this cell is zinc, and the electrolyte a solution of potassium hydrate, or caustic potash. Two plates of zinc are used in most forms of this cell, one on each side of the cupric-oxid plate.

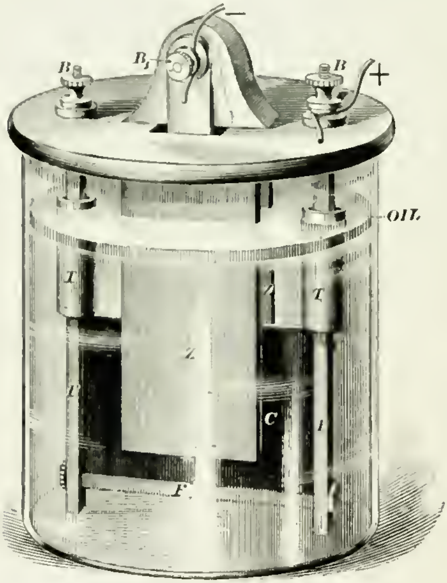

FIG. 11.

A cell of this type, having a capacity of 150 ampere-hours, is shown in Fig. 11. The cupric-oxid plate C is suspended in a copper frame F, F between the two zinc plates Z, Z, which are hung from each side of a lug on the porcelain cover of the jar. The sides of the copper frame of the oxid plate are carried up

through the cover supporting the plate, and form terminals B, B, either of which may be used as the positive terminal of the cell. That part of the copper frame which projects above the plate C is protected from the action of the liquid by tubes of insulating material T, T. A binding-post B_1, on the bolt that supports the two zinc plates, serves as the negative terminal. A layer of heavy paraffin oil is used in this cell to prevent the action of the air on the solution.

The 150-ampere-hour cell, shown in Fig. 11, is $5\frac{1}{4}$ in. $\times$ $8\frac{1}{4}$ in. outside dimensions, and will give a current of 3 amperes at a potential of about .7 volt for 50 hours, which is equivalent to about 100 watt-hours, with one "charge" of zinc, caustic potash, and oxid The internal resistance of the above cell is about .07 ohm ; the weight of the oxid plate is about $\frac{1}{4}$ pound. They are very constant and are able to furnish a large current ; the local action is small.

DRY CELLS.

50. Construction and Use.—This name is applied to cells, usually belonging to cells having a solid depolarizer, in which the electrolyte is carried in the pores of some absorbent material, or combined with some gelatinous substance so that the cell may be placed in any position without spilling the liquid. These cells are generally made in small sizes, with zinc and carbon elements, the zinc, usually forming the outside of the cell, being made into a sort of cylindrical can, in the center of which is the carbon, surrounded by its depolarizing compound. The space between them is filled with some absorbent material, such as "mineral wool," asbestos, sawdust, blotting-paper, etc., and the whole is then soaked in the exciting liquid. In some the exciting liquid is mixed with a hot solution of some gelatinous body, such as isinglass or "Irish moss," which mixture is poured into the cell, and on cooling it forms a soft jelly. The first method of preparation is that most used.

It is evident that only a comparatively small amount of liquid can come in contact with the zinc at one time, hence the current-strength is not as great as that of an ordinary cell ; they are therefore more adapted for smaller currents and for

intermittent work. It is quite necessary, however, that they have a depolarizer, as otherwise they must be made open to allow the hydrogen to pass off, and this would allow the small amount of water they contain to evaporate. To prevent evaporation, the cells are sealed with some resinous compound.

The materials used in dry batteries are usually kept secret by the manufacturers; they all, however, answer to the above description as to construction, and the best types employ the same materials as the Leclanché battery; that is, a zinc element, an ammonium-chlorid electrolyte, manganic oxid or binoxid of manganese as a depolarizer, and a carbon element.

Some of these cells act very satisfactorily and are quite suitable for medical work, by reason of their portability and the small amount of attention and care required. If properly cared for, that is, if not used too much beyond their capacity, they will last from a year and a half to two years, when they must be replaced by new cells. The smaller sizes weigh as little as 8 ounces, and measure $1\frac{1}{2}$ in. × $1\frac{1}{2}$ in. × $3\frac{3}{4}$ in.; their E. M. F. is about 1.5 volts and their internal resistance .65 ohm. A larger size has a resistance of only .25 ohm, and two of these used in parallel are sufficient to heat a short platinum wire for cautery-work to a white heat, and may also be used for operating induction-coils.

51. The Burnley Cell.—One of the best known dry cells in this country is the *Burnley* cell. This has a central carbon rod, surrounded with a paste of manganese peroxid and powdered carbon, which is moistened with a solution of zinc chlorid and sal ammoniac. Between the exterior casing of zinc and this central core is another paste composed of plaster of Paris and flour, moistened with the same solutions mentioned above. The whole is sealed on top by some pitch-like compound. The outside of the cell being one element, care must be taken not to bring it in contact with other cells or conductors, and the cell is therefore inserted in a case of millboard. A cell weighing 2 pounds 1 ounce, with an E. M. F. of about 1.45 volts, is able to send a current of .1 ampere for 200 hours, and can do this before the E. M. F. will fall below .5 volts.

THE APPLICATION OF PRIMARY BATTERIES.

52. Cost.—It was stated above that the cost of producing an E. M. F. by chemical means was far beyond that generated by motive power. But there may be cases where these conditions are reversed, when, in fact, it costs less to use primary batteries. Of course, these latter can never compete with motive power when it is a question of large units and constant supply. but when only a small current is needed at long intervals, and where in the meantime no material is consumed, the cost of the material is entirely offset by the small amount of attention required and the constancy of the source of supply.

The current from cells is much used for medical work ; currents of a few milliamperes in strength, but of from 75 to 100 volts E. M. F. are applied for curative purposes ; while currents of from 10 to 20 amperes in strength are used for heating cautery-loops in surgical operations, requiring an E. M. F. of from 4 to 8 volts. Miniature incandescent lamps are also employed to examine the various cavities of the body. Obviously, if the cells selected have a high E. M. F. (say, 2 volts), a less number will be required than if the cells are of a low E. M. F.

53. For furnishing the larger currents for cautery-work, large cells should be selected, those which are so arranged as to have a minimum internal resistance being best. As the use of porous cups in a cell increases the internal resistance largely, cells that employ them are not well suited for this work. Grenet cells are therefore very convenient for this purpose, as the resistance is low and the E. M. F. high and steady.

54. Mechanical Construction.—Attention must also be paid to the mechanical construction of the cells selected, as on this point often depends their life and suitability for the work they are called upon to perform.

The binding-posts should be firmly and substantially fixed to the elements, and should be thoroughly protected from possible contact with the electrolyte, as the resulting action will so corrode the joint between the two as to destroy the

contact, besides possibly eating away the connecting wires and breaking the circuit. Each binding-post should be provided with two openings for the reception of rheophores, or conducting wires; this will often save time and annoyance.

As much as possible of the material of the positive element should be below the level of the liquid, for when that is consumed the balance must be thrown away, and this may represent a considerable loss.

55. Consumption of Material.—In general, it must be remembered that the consumption of material in a primary cell (assuming no local action) is proportional to the output in ampere-hours; the *energy* output depends not only on the amount of material consumed but on the E. M. F. of the cell and its internal resistance, so that, other things being equal, the higher the E. M. F. of a cell and the lower its internal resistance, the greater its output for a given cost of material.

56. Internal Resistance.—It is evident that all the E. M. F. of a cell is not available to send a current through the external circuit, but that a part is expended in overcoming the internal resistance. If the external resistance is very great, as when sending a current through the human body, this E. M. F. expended in overcoming internal resistance is of little importance. On the other hand, if the external resistance is very small, as in cautery-work, the internal resistance practically determines the amount of current flowing. To obtain the maximum current-volume in an electric circuit, the external and internal resistance should be about the same.

SECONDARY BATTERIES, OR ACCUMULATORS.

57. Construction.—A *secondary battery*, *storage-battery*, or *accumulator*, as it is variously called, consists of an apparatus in which certain materials are so arranged that when a current is passed through the apparatus these materials are able to rearrange themselves in such a manner as to be able to act as a voltaic cell, and by chemical action produce electrical energy. Accumulators store *energy*, but not *electricity*, by converting the

kinetic energy of the electric current into *chemical potential energy*, which may be realized again as kinetic energy.

Many forms of primary batteries may, when exhausted, be more or less regenerated by passing through them a current from some external source, in the opposite direction to the current they themselves produced. This current passed in the opposite direction restores the elements and the electrolyte of the cell to the condition in which they were before being used. It is customary, however, to consider as accumulators only those cells whose original construction is similar to an exhausted battery; that is, they cannot be used as sources of electricity until they have been *charged* by passing a current through them.

58. Positive and Negative.—Some confusion exists as to the use of the terms *positive* and *negative* in speaking of the plates of a secondary cell; for, in charging the cell, the current is in the reverse direction to that which flows when the cell is acting as a voltaic cell and discharging. It is customary, however, to speak of the plate at which the current enters the cell (while charging) as the positive plate. In fact, whether charging or discharging, this plate is at a higher potential than the other, which justifies the above use of the term, although, with respect to the chemical actions in the cell, the positive and negative plates are reversed in the two operations.

59. Classes of Accumulators.—Accumulators may be divided into two general classes: (1) *lead accumulators* and (2) *bimetallic accumulators*. The larger proportion of cells now in use are of the first class.

LEAD ACCUMULATORS.

60. Construction.—The original lead accumulator, as made by Planté, consists of two plates of lead, usually rolled together in a spiral and separated by strips of rubber or other suitable insulating material; these are placed in a ten-per-cent. solution of sulfuric acid. On sending a current from some external source through the cell, the water becomes decomposed,

and the oxygen combines with the positive plate, forming lead oxid or peroxid, while the hydrogen collects at the negative plate. On disconnecting the source of the charging-current, and completing the external circuit of the cell, the water is again decomposed, the oxygen uniting with the hydrogen collected at the negative plate, and also with the lead plate itself; and the hydrogen uniting with the oxygen of the oxid of lead at the positive plate, thus producing a current in the opposite direction to that of the charging-current.

61. Oxidation.—Owing to the fact that the formation of the layer of oxid prevents further oxidation, the amount of chemical change due to the charging-current is small, so that the secondary current from the cell is of short duration. After this current has ceased, however, the surface of the positive plate is much increased, owing to the removal of the oxygen from the lead oxid, leaving the metallic lead in a spongy form. On again sending a current through the cell, a further oxidation of this (positive) plate takes place, and by continuing this process, reversing the current each time it is sent through the cell, both positive and negative plates become porous to a considerable depth; this very much increases the surface on which the oxidation can take place. This process might be carried on until the whole plate is reduced to spongy lead; in that case the plate would not hold together, so a sufficient amount of the original plate must be left for mechanical strength. After the plates are so *formed* they are ready to be used as an accumulator.

62. The Faure Process.—This forming process, however, is too long and expensive for commercial success, though it may be considerably hastened by roughening the surface of the lead plates with nitric acid before commencing the process. It was soon superseded by the process, invented by Faure, of coating the surface of the plates with some substance that, by the first charging-current, is converted into lead peroxid on the negative plate and into spongy lead on the positive. This substance may be lead oxid (litharge), lead sulfate, minium (Pb_2O_3), lead peroxid, or a mixture of these substances.

63. Grids.—These substances are applied in various ways. One method is to make a paste of the substance (in this case, usually minium), that for the negative plate being made with sulfuric acid—which changes the Pb_2O_3 into $PbSO_4$ (lead sulfate)—and water, while that for the positive plate is made with water only. These pastes were originally applied directly to the surface of the plain lead plate; but as they proved to be only slightly adhesive, the plates were prepared by scratching or otherwise roughening the surface, which process has been gradually extended until the lead plates are now cast into *grids*, or latticework plates, into the spaces of which the paste is put or forced by hydraulic pressure. Some manufacturers do not use a paste of the active material, but employ minium, litharge, or lead sulfate in the form of dry powder, forcing the powder into the grid under such enormous pressure that it is solidified.

64. After the grids have been filled with active material, they are set up in pairs, in suitable vessels, and surrounded with an electrolyte consisting of dilute sulfuric acid having a Sp. Gr. of 1.17, which density corresponds to about 20 per cent. of acid in the liquid. A *charging-current* is then sent through the cell from some external source; the action of this current decomposes the water, the oxygen of which further oxidizes the lead oxid to peroxid at the positive plate. The hydrogen goes to the negative plate, where it reduces the lead sulfate to spongy lead by uniting with the SO_4, forming sulfuric acid. Thus, the active material becomes lead peroxid in the positive, and spongy lead in the negative, plate.

65. Gassing.—When the active material is thus all converted, continuing the charging-current produces no further effect, except to continue to decompose the water; the resulting gases then pass off through the water, giving it a milky appearance. This phenomenon is known as *gassing*, and it is an indication that the cells are fully charged. Continuing the charging-current beyond this point—that is, overcharging the cells—does no harm to the plates, but the energy represented by the current is wasted.

66. On discontinuing the charging-current at the gassing point, and completing the external circuit of the cell, a current will flow in the opposite direction to that of the charging-current, the resulting chemical action being to reduce the lead peroxid to lead oxid at the positive, and the spongy lead to lead sulfate at the negative, plate; a secondary action is the formation of a part of the lead oxid at the positive plate into lead sulfate. The sulfates thus formed are not all of the same proportions; one exists as red, another as yellow, and a third as white, crystals. Of these the white sulfate is best known, as it is formed when the cell is considerably discharged, and is extremely troublesome. This discharge may be continued until all chemical action ceases, and the E. M. F. consequently falls to zero; but this is not advisable, since, if the discharge is carried beyond a certain point, the red or yellow sulfates, probably by combination with the litharge (PbO), form the white insoluble sulfate, which has a higher proportion of lead than the others; and this, being a non-conductor, naturally increases the internal resistance of the cell, and, when it is removed, usually carries some of the active material with it, as it is very adhesive.

67. Sulfating.—When the cells have been properly charged, the positive plate is of a brown or deep-red color, while the negative is a slaty gray. The presence of the insoluble sulfate is made apparent by the formation of a white coating or glaze over the plates, which are then said to be *sulfated*. If the cells are discharged and left to stand with the electrolyte in place, sulfating takes place rapidly.

As sulfuric acid is formed while charging, the density of the electrolyte will vary with the state of charge of the cell. When fully charged, the specific gravity will have changed from 1.17 to 1.22, but during discharge it will again return to its previous density.

The E. M. F. of this type of cell is approximately 2 volts, which gradually falls to 1.9 volts when nearly discharged. Beyond this point, further discharging causes the E. M. F. to fall more rapidly, the decrease after 1.8 being very rapid.

68. Buckling.—Notwithstanding the fact that accumulators are usually based on their capacity, when discharged to an E. M. F. of 1.8 volts, a long series of tests shows that they should not be continually discharged below 1.9 volts, as below this point *sulfating* is very liable to occur, and, the nature of the chemical action being changed, it leads also to the distortion of the positive plate, known as *buckling*. The buckling is liable to cause the plates to touch and thus to short-circuit the cell.

69. The cause of buckling seems to be the formation of a sulfate in the plugs of active material that fill the spaces of the grids, thus causing the plugs to expand ; lead having very little elasticity, the grid is forced out of shape. As usually constructed, the edges of the grid are heavier than the intermediate portion, so that the effect of the distortion is to bulge the plate in the center. If the plates are not discharged too far and too rapidly, the expansion of the active material is gradual, causing the grid to stretch evenly ; this makes the plates "grow," or increase in area, sometimes as much as 10 per cent.

70. The amount of material altered by chemical action in a completely charged cell determines the *quantity* of electricity which it may furnish ; while the surface of the active material exposed to the chemical action determines the *rate* at which the material is altered, and, therefore, the *strength* of the current in amperes. Cells of this type are rated at a certain number of *ampere-hours* capacity, depending both on the weight and on the surface area of the active material in the cell. A certain economical *discharge rate* is also recommended, depending on the surface of the plates exposed to the electrolyte.

71. Ampere-Hours.—*Ampere-hours* is the product of the current-strength in amperes and the number of hours during which the current will flow before the capacity of the cell is exhausted. For instance, 100 ampere-hours means that a current of 100 amperes will flow for one hour, or 4 amperes for 25 hours, or any other combination the product of which is 100.

But it must not be supposed that with a given number of ampere-hours it is immaterial at what rate the battery is discharged. On the contrary, there is for each size a certain

rate beyond which it is not advisable to go, and, if this discharge rate is continually exceeded, the chemical action goes on too rapidly, the white sulfate is formed in the active material of the positive plate, finally causing disintegration of the active material and buckling of the plates, even if the discharge is not carried beyond the point (1.9 volts E. M. F.) mentioned above. With the ordinary construction, the normal discharge *rate* is about .033 ampere per square inch of the positive plate, and the discharge *capacity* about 4.5 ampere-hours per pound of plate (both positive and negative plate included).

72. Output.—It is evident that the interior portions of the active material are affected much more slowly than the surface, as the acid penetrates the active material only at a comparatively slow rate. Reducing the rate of discharge therefore gives the active material more time to be uniformly and thoroughly reduced, thus giving a greater output. This is also the reason why the E. M. F. rises to its original value, if the discharge is interrupted at any point before a complete discharge has taken place.

If a cell is discharged at a rate beyond that most suitable for it, the output in ampere-hours will be reduced. Conversely, if the rate had been lower, the output would have been increased.

For example, assume the limiting E. M. F to be 1.9 volts. In a certain cell, with a discharge-current of 30 amperes, the E. M. F. reaches its limit in 10 hours, giving an output of 300 ampere-hours. If the discharge-current were 40 amperes, the limiting E. M. F. would be reached in about $6\frac{1}{2}$ hours, giving an output of only 260 ampere-hours; while, if it were 20 amperes, the limiting E. M. F. would not be reached for about $17\frac{1}{2}$ hours, giving an output of 350 ampere-hours.

73. Efficiency.—The *efficiency* of the accumulator (or of any means of storing or transforming energy) is the *output* divided by the *input*. This quotient is always less than 1, as the accumulator is not a *perfect* storer of energy.

The *input* and *output* of an accumulator may be expressed either in ampere-hours (the quantity of electricity) or in watts (the *rate of doing work* of the current). If the cells be discharged

at a normal rate, the *ampere-hour efficiency* will be ordinarily from .87 to .93, or 87 to 93 per cent. The *watt efficiency* at normal rate of discharge is lower, being from 65 to 80 per cent., depending on the construction of the cell. In a larger cell it may be as high as 84 per cent.

74. Loss Due to Internal Resistance.—The loss due to the internal resistance in well-designed cells usually amounts to about 8 per cent. at normal rate of charge and discharge. In a good modern cell, exposing 1,100 square inches of positive-plate surface, the internal resistance is about .005, when charged. Cells of greater capacity than the above (which is listed as 350 ampere-hours) would have a proportionately lower resistance.

75. Care of Cells.—If an accumulator of this class is not discharged at an excessive rate, nor to more than 1.9 volts E. M. F., the positive plates should last for about 1,200 or more discharges; while, if discharged each time to below 1.8 volts, or at excessive rates, the life of the positive plate will not ordinarily be more than 400 or 500 discharges. The negative plates, with good care, will usually outlast four or five positive plates.

76. There are several other kinds of treatment that will damage the cells. Among these is the habit of connecting the poles through a small resistance, to see if the cells are in good order. A current of great magnitude will flow for a moment and it will be likely to loosen the paste and cause sulfating in the cell. Either a voltmeter or a small incandescent lamp should be used for this purpose. When the cells are used for heating a large cautery, they should not be turned on suddenly, but gradually, by means of a variable resistance.

77. Construction of Cells.—The usual construction of the cells is as follows: The plates and electrolyte are contained in a vessel of an approximately cubical form; this vessel is of glass, if the cells are not intended to be portable, as the glass allows the condition of the plates to be ascertained while the cell is in operation. If the cells are intended to be portable, the vessel is usually made of hard rubber, or of wood lined with

hard rubber or lead. The plates are usually approximately square, and from $\frac{1}{4}$ to $\frac{1}{2}$ inch thick, according to size. To get a large surface area without using single large plates, and to allow of one size of plate being used for cells of various capacities, each cell contains a number of positive and negative plates, arranged alternately, side by side, a short distance apart. The number of negative plates is always one more than the number of positive plates, so that *each side* of each positive plate has presented to it the surface of a negative. All the positive plates are connected together by a connecting strip, usually at one corner of the plate, and all the negative plates are similarly connected. The arrangement of a typical accumulator-cell is represented in Fig. 12, where the plates marked N are negative and those marked P are positive. From a corner of each plate a lug projects; the lugs on the negative plates are joined to a connecting strip, as represented at T, and the lugs on the positive plates are similarly joined to a connecting strip T'. These connecting strips are extended beyond the limits of the cell, and serve to connect the various cells of the battery together, as shown at C, the connection being made by a brass bolt, which firmly clamps the connecting strips together.

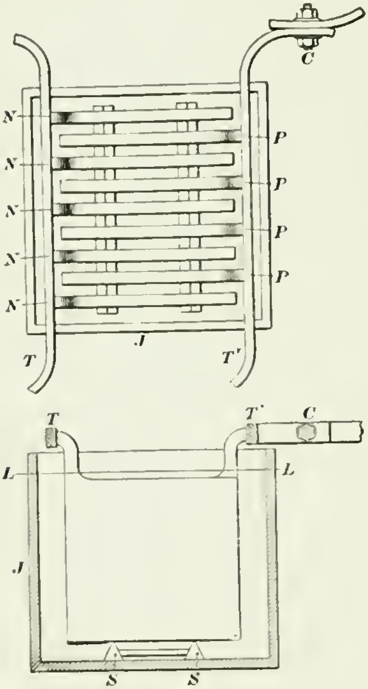

FIG. 12

The plates are placed in the jar J, and they rest on a support made from two strips of wood (usually boiled in paraffin) of triangular section S, S. These support the plates at such a height that any loosened particles of active material fall

below the level of the bottom of the plates, thus preventing possible short-circuiting. When in position, the electrolyte is poured in until it reaches the line $L L$, thus covering the plates. The plates are usually kept separate by blocks of insulating material.

78. The Tudor Grid.—There are many variations of the improved Faure type, but only a few examples will be given. They all avoid the expense of *forming* the plates by utilizing the so-called "pasted plates."

Fig. 13 (a) represents a section of the *Tudor* grid, a form of pasted-plate grid that has many good features; it is composed of a number of small square or rectangular grooved grids G, about 6 inches square, with the active material pasted or forced into the grooves as in the ordinary form [see section Fig. 13 (a) taken on line $a b$]. Six or more of these small grids are then fastened by a lug on one edge, as at C, to the bars of the supporting frame F, made of cast lead, which has openings between the bars slightly larger than the small grids which they enclose. The small grids are thus free to expand or contract without interfering with the plate as a whole, thus preventing, to a large extent, the buckling and the disintegrating of the plate, and any damaged grid may be replaced without disturbing those remaining. None of the pasted-plate cells, however, are as substantial as those in which the active material is formed from the plate itself, as in the Planté cell. Accumulators employing this form of grid are largely used in Germany and Belgium, and also form one of the largest accumulator installations in the United States, that of the Edison Electric Illuminating Co., Boston, Mass., which consists of two sets of 70 cells each, having a capacity of about 3,500 ampere-hours per set.

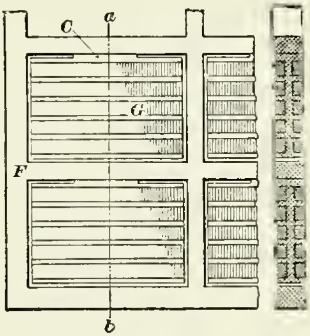

FIG. 13 (a).

79. The Chlorid Accumulator.—A form of cell in which the plates, it is claimed, combine the cheapness of preparation of the pasted plate with the greater solidity and longer life of the Planté plate, is the *chlorid accumulator*. The plates of this type of cell are made as follows: A mixture of zinc chlorid and lead chlorid is melted and run into molds, which form it into cylindrical pellets, or pastils. These have a bevel-shaped edge. The pellets are placed in a second mold, being held in position by steel pins, and an alloy of lead and antimony is melted and forced in between the pellets, under heavy pressure. When this cools it forms a plate, binding all the pellets of zinc and lead chlorid together.

80. This plate cannot be used in this form in an accumulator; a number of these are first set up in a bath of dilute zinc chlorid with plates of zinc, to which the lead plates are connected. These plates then act as the elements of a primary battery, and the resulting chemical action dissolves the zinc chlorid contained in the pellets, and converts the lead chlorid into metallic lead, which assumes a crystalline form. The plate is now practically a continuous lead plate, solid and dense in some parts and porous in others. The plates in this condition are suitable for negative plates; those required for positive plates are then set up with plain plates in a bath of dilute sulfuric acid, and a forming current sent through them from the prepared to the plain plates. This current causes the porous parts of the plates to be formed into lead peroxid and into lead sulfate; the plate is now the equivalent of a pasted plate, and is an improvement through having its active material firmly bound in place in the composite grid.

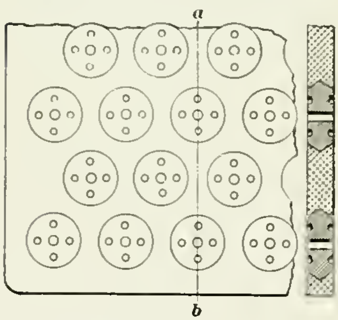

FIG. 13 (*b*).

Fig. 13 (*b*) shows a part of one of these plates; the section taken along the line *a b* shows the shape of the plugs. The

holes in the plugs are caused by the pins by which they are supported in the mold. The requisite number of these prepared plates are then set up together to form a cell, positive and negative plates alternating and being connected to common conductors, as in other types of cells. (See Fig. 12.) The plates are each surrounded by a sheet of asbestos paper, and are separated from each other by a thin wooden strip, so thoroughly perforated with large holes that it really fills little of the space between the plates.

81. The E. M. F. of this form of accumulator is the same as that of the Faure (pasted) type or the Planté. It is claimed by the manufacturers that, because of the solidity of the construction, buckling and loosening of the active material are practically impossible, so that the cells may be discharged to a low E. M. F. or at high rates without serious injury. Its output per pound of element is greater than that usually assigned to lead accumulators, being about 5 ampere-hours per pound of plates (both positive and negative) at normal discharge rates.

BIMETALLIC ACCUMULATORS.

82. Classes.—In this class of cells the elements consist of two different metals, the electrolyte being a salt of one of the metals. There have been several combinations of materials proposed for cells of this type, but the only cells that have been actually used to any extent are the zinc-lead, copper-lead, and copper-zinc cells.

83. Zinc-Lead Cells.—The *zinc-lead* cell usually consists of plates of zinc and lead in a solution of zinc sulfate. When being charged, the zinc sulfate is decomposed, depositing zinc on the zinc plate and forming nascent sulfuric acid with the hydrogen of the water, which is also decomposed, its oxygen uniting with the lead plate, forming peroxid of lead. This nascent sulfuric acid slowly attacks the deposited zinc, both on open circuit and while charging, so that the efficiency of the cell is low and it will not retain its charge more than a few

days. The E. M. F. is high, being about 2.35 volts. The more modern forms of this cell employ a tinned-iron plate, amalgamated, or a lead plate, in place of the zinc plate.

84. Copper-Zinc Cells.—The copper-zinc accumulators are in more general commercial use than the other forms of bimetallic cells, the best known being the Phillips-Entz accumulator. This accumulator employs the same active materials as the Lalande-Chaperon or Edison-Lalande primary cell (see Art. **49**), modified in mechanical construction to adapt them for accumulator use. The efficiency of this type of accumulator is about the same as that of the lead accumulators, while its output is very much greater, weight for weight, the ampere-hour output being about five times that of a lead cell, or about 20 ampere-hours per pound of plate; but local action is liable to occur on open circuit, so that these cells will not retain their charge for more than a few days, while a lead accumulator will scarcely lose 25 per cent. of its charge in as many months. On account of these features the copper-zinc accumulator can only be successfully used in installations where it is charged and discharged daily.

85. Other forms of bimetallic accumulators have been proposed, and in some cases used, among which may be classed several forms of primary cells, such as the Daniell, Leclanché, and others, which may be "regenerated" by passing a current through them; these have never been of commercial value, and do not require further attention.

USES OF ACCUMULATORS.

86. Advantages.—When, for medical purposes, a current of considerable strength is occasionally required, with long intervals between, accumulators constitute an ideal source of electric power. Primary cells might be directly applied in such cases, but on account of their high internal resistance either a considerable number of small cells or a few large cells would be required to furnish the necessary current. If, however, primary cells, say of the gravity or other type, giving a

constant E. M. F., are used to charge secondary cells, the charging can go on continuously day and night at a slow rate, and at any time the secondary cells may be drawn upon for a considerable current, far beyond the capacity of the primary cells themselves. This method is often adopted in surgeons' offices, where a considerable current is occasionally required for cautery-work or other purposes.

87. The Charging-Current.—It has been found that in charging an accumulator only a small part (about 8 per cent.) of the E. M. F. required to force the current through the cell is expended in overcoming the resistance of the plates and the electrolyte; the remainder is expended in overcoming the E. M. F. of the chemical action of the cell. It follows, then, that, if the *applied* E. M. F. be just equal to the E. M. F. of the cell, no current will flow, so that the E. M. F. of the cell itself may be considered as a counter E. M. F. opposing that of the charging-current. To apply Ohm's law $\left(C = \frac{E}{R}\right)$ to this case, E must be considered as representing the *algebraic sum* of the applied and the counter E. M. F., or E = applied E. M. F. — counter E. M. F. This is another way of saying that the E. M. F. *required to drive the charging-current through the cell* is not only that required to overcome its ohmic resistance, but that to this must be added an E. M. F. equal and opposite to the E. M. F. of the cell itself, due to the chemical affinity of the substances of which it is composed.

In charging, then, if from any cause the E. M. F. of the charging-current be changed by a small amount, the charging-current will be altered in a much greater degree, depending on the ratio between the applied E. M. F. and the difference between the applied and the counter E. M. F. For example, consider a cell that has been discharged until its E. M. F. is 1.925 volts (on open circuit). The resistance of the cell is .005 ohm and its normal charging-current is 35 amperes. The drop in voltage due to this current is $35 \times .005 = .175$ volt; the applied E. M. F. must then be $1.925 + .175 = 2.10$ volts, in order to cause 35 amperes to flow. If the applied E. M. F.

drops to 2.0 volts, it is evident that, the counter E. M. F. being the same, the available E. M. F. is $2.0 - 1.925 = .075$ volt, and the current that this E. M. F. would be able to drive through the cell is $C = \frac{E}{R} = \frac{.075}{.005} = 15$ amperes. Thus, a drop in the applied E. M. F. of $\frac{.1}{2.1}$, or about 5 per cent., causes the current to fall off more than 50 per cent. This shows the necessity of having the source of the charging-current so arranged that the E. M. F. may be closely adjusted, in order that the charging-current may be maintained at its proper value.

88. Density of the Electrolyte.—A *hydrometer* should be used to ascertain the density of the electrolyte. The volume of the electrolyte will gradually diminish during the operation of the cell, due to evaporation and to the evolution of gas when the cell is charged; this loss should be made up by occasionally adding pure water or acid if the density, as indicated by the hydrometer, is too low.

89. Measurement of the E. M. F.—A *portable voltmeter* should also be provided which shall have a capacity such that the E. M. F. of a single cell may be accurately measured, so that, if the action of any cell seems to be irregular, its condition may be determined by measuring its E. M. F. and comparing it with that of the other cells.

SELECTION OF A BATTERY.

90. General Treatment.—It is not easy to select the proper cells for medical purposes. An ideal cell for both portable and stationary batteries would be one that is cheap, light in weight, and in little need of attention; but all these attributes are not found in one cell, and compromises must therefore be made. For a stationary battery, the size of the cell might not make much difference. When it comes to portability, the "dry" cells would seem to be the most suitable, but practice demonstrates that the red-acid battery renders the best service.

91. Cautery and Lighting.—For *cautery* work and for *lighting* small incandescent lamps, then, undoubtedly a 2- and a 4-cell accumulator, respectively, will be the most serviceable. They ought to have a switch for arranging the cells in parallel or in series, and also an adjustable resistance. Should there be difficulties in recharging the battery, then a large-sized bichromate battery of, say, from 4 to 6 cells, may replace it. It is not advisable to have too many different kinds of batteries. It is better to make one battery serve as many purposes as possible; there will then be less expense for maintenance and less trouble in caring for them. The Daniell cell, the bichromate cell, or the Edison-Lalande may be used to recharge an accumulator, if no other means are at hand.

CARE OF BATTERIES.

92. Renewals.—In the care of batteries, there is little to add to what has been already said. A dry cell needs no attention so long as its E. M. F. remains constant; as soon as the latter begins to fall off very materially, the cell needs to be renewed. This is a distinct disadvantage, because one must always send to the manufacturers for a new cell. Edison-Lalande cells will work without further attention until exhausted, when new plates and solutions must be put in. The Leclanché cells also require little care except an occasional addition of water to replace the amount lost by evaporation. Any tendency of the exciting liquid to creep over the edge of the cell must be prevented by coating the exterior of the upper part of the cell with paraffin wax. The red-acid cells last much longer when a small amount of mercuric bisulfate is added to the electrolyte.

93. Contact Surfaces.—When an acid enters into the composition of an electrolyte it is apt to cause trouble because of its tendency to oxidize the metallic surfaces connected with the cell. All oxids are poor conductors, hence the necessity of removing them with a piece of emery-cloth. As a contact surface cannot be too bright and free from all greasy

substances, it is important to give the connections a great deal of attention. Should there be any suspicion about the contact surfaces of the connections, they must be rubbed with a piece of emery-cloth, and the various screw connections made tight to make certain that they will remain in good contact. It has already been said that the zincs must be amalgamated, and care must be taken that they remain so.

94. Care of Bichromate Cells.—It is less easy to take care of the bichromate cells and to know when the electrolyte needs renewing; but as a rule this ought to take place when its color is a dark green. Should the color of the electrolyte be orange, and the cell yet show some weakening in its action, then the addition of some sulfuric acid may improve it. If the bichromate cells are used daily, the electrolyte will need renewing in from three to six weeks. The elements should then be removed and suspended in a jar with cold water in which about a tablespoonful of salt has been dissolved; the water should not be permitted to wet the switchboard. Most of the impurities in the carbon will be dissolved when the water has assumed a greenish hue. After a thorough soaking, the elements are rinsed off in cold water and thoroughly dried with a rag. They are then replaced in the battery. The importance of lifting the zincs out of the electrolyte when not in use has already been dwelt upon.

95. Care of Electrodes.—When the battery has been used, the electrodes should never be thrown down in a careless manner, as either the battery as a whole or one of the cells may be short-circuited. Such a short circuit is deleterious to all batteries and to dry batteries in particular. The latter are in most cases permanently damaged by short-circuiting them, because the polarization that will take place is so excessive as to make it impossible for the cells to again recuperate. A few minutes of this accidental contact is enough to cause the damage; it is therefore advisable to form a habit of placing the electrodes in a proper position, where short-circuiting is impossible. Attention must also be given to the insulating covering of the

electrodes. After frequent use the insulating material will wear through, or it may be, at any time, accidently injured. In this case, the bare conductor may make contact with one of the metal connections and cause a short circuit. It is likewise possible that some instrument may in a hurry be laid down on the switchboard and make an unintentional contact between separate connections.

96. The Poles.—After a battery has been disconnected for the purpose of cleaning or renewing, it is important to see that the connections are properly made and that the poles have not been reversed. Should there be any doubt on this point, it is well to make certain that the positive electrode has been connected to the positive binding-screw of the switchboard. For this purpose various pole-testers may be used; or a piece of litmus paper may be placed on a piece of glass and inserted under the ends of the two electrodes without letting the latter touch each other. Acid will be liberated at the positive pole and will redden the blue paper, while under the negative pole the red paper will turn blue.

ELECTRIC CIRCUITS.

CLASSIFICATION OF ELECTRIC CIRCUITS.

97. The Voltaic Cell.—Before proceeding to the consideration of means, other than cells, employed in the production of an electromotive force, it is advisable to first consider the voltaic cell in connection with conductors of various resistances.

98. Circuits.—We have already seen, when studying Ohm's law, the general effect of an E. M. F. and of a resistance on the strength of an electric current; but there are certain other effects produced by the installation of a voltaic cell in a circuit, which call for very careful consideration, particularly

as such combinations play a very important part in medical treatment.

1. *What is a Circuit?*—First let us consider the meaning of the word *circuit*. It is evident that a battery, in and by itself, is of no utility as a therapeutic agent ; it must, by means of a conductor, be brought in communication with some device or substance that is to be affected by the electric current. Let it, for instance, be supposed that a cautery is to be heated ; then the positive binding-screws of the battery and cautery are connected together by one wire, and the negative binding-screws by another one. We have then what is termed a *circuit*—that is, a combination of an electric source with conductors and various receptive devices arranged in such a manner that the electric current is allowed to leave the source at one terminal, traverse the various conductors and devices, and return to the source at the other terminal. The whole path is the *circuit*, and it is said to be *closed* so long as the current is permitted to pass, and to be *open*, or broken, when the current is interrupted at some part, preventing a flow of electricity. In order that a current may flow, there must always be a closed circuit.

2. *Grounded, or Earth, Circuits.*—When the earth or ground forms part of a circuit it is called a *grounded circuit*, or an *earth circuit*. Such connections are made when electrostatic machines are used, and are also utilized in telegraph lines.

3. *External and Internal Circuits.*—That part of a circuit which is external to the electric source is called the *external circuit*, while the remaining part of the circuit, included within the electric source, is called the *internal circuit*. For instance, in the case of the simple voltaic cell, the internal circuit consists of the two metallic plates, or elements, and the liquid, or electrolyte ; the external circuit would be some external body, as part or whole of the human organism, and the conductors by means of which it is connected to the cell.

4. *Divided Circuits.*—When a circuit divides into two or more branches, as in Figs. 23 and 24, where each branch transmits part of the current, it is called a *divided* circuit ; the branches are said to be connected in *parallel*. Each branch taken separately is called a *shunt*.

5. "*Parallel.*"—Fig. 14 (*a*) is an example of cells connected in *parallel.* Here the positive terminals of all the cells are connected to one main positive conductor and all the negative terminals are connected to one main negative conductor.

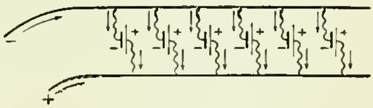

Fig. 14 (*a*).

6. "*Series.*"—When the cells are so connected as to allow the current to pass successively through each, they are said to be connected in *series.* This combination is shown in Fig. 14 (*b*), in which a battery of voltaic cells is arranged in one circuit by joining the positive terminal of one cell to the negative terminal of the adjacent one, so that the entire current passes successively through each cell.

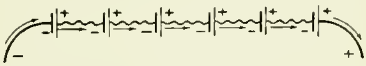

Fig. 14 (*b*).

7. "*Parallel Series.*"—The connections between cells, lamps, or other devices may also consist of a combination of the two previous classes. This may be accomplished as in Fig. 15, where several cells are made up in groups in which the cells are connected with one another in series, and these various groups are then connected in parallel. This combination constitutes a *parallel-series* circuit.

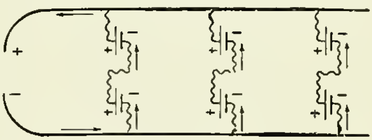

Fig. 15.

8. "*Series Parallel.*"—If the cells in the separate groups are connected with one another in parallel, and the groups then joined in series, we have a combination called a *series-parallel* circuit. An example of this is given in Fig. 16.

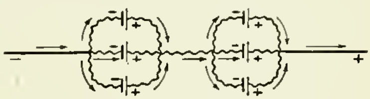

Fig. 16.

99. It is evident that, in a combination in which a battery constitutes part of the circuit, the battery is not only acting as a source of E. M. F., but constitutes also a part of the total resistance of the circuit. We shall see later on that this internal resistance of the battery is under certain conditions very effective, and in many cases determines the most suitable

arrangement of cells for the production of the proper current-strength.

100. When electromotive force was described and illustrated by means of Fig. 1, its general effects were considered only so far as they related to the starting of an electric current. We shall now proceed to consider more fully the variations an E. M. F. undergoes in passing from one part of a circuit to another.

LOSS OF ELECTROMOTIVE FORCE IN A CLOSED CIRCUIT.

101. "Watermotive" Force.—As soon as a voltaic cell begins to send a current through a circuit, there immediately arises in its path an obstacle in the form of a resistance

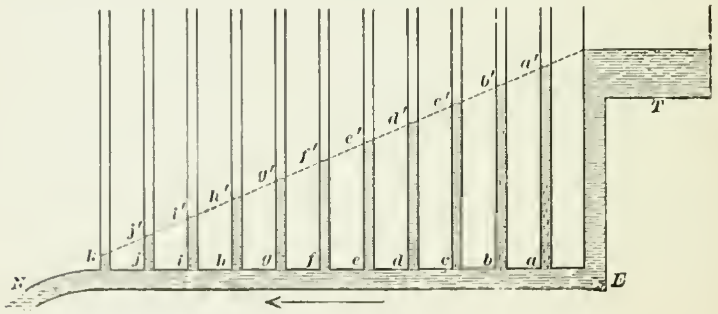

FIG. 17

which has to be overcome; this can only be done by a certain expenditure of electromotive force. To make this more clear, we will again use as an analogy the flow of water in a pipe. In Fig. 17, *T* is a tank of water communicating with the pipe *E N*. If water is permitted to flow through this pipe, the quantity of water that passes at any point of the pipe will be the same, and the rate of flow, or the quantity that passes any point in 1 second, will also be the same so long as the level in the tank remains at the same height. Should the supply be insufficient and the level fall, then the flow would still be uniform in all parts of the pipe, but less water would flow through the pipe as a whole; that is, the rate of flow would be smaller. Although the *flow* is uniform, *the pressure per square*

inch at the various parts of the pipe would not be the same. To convince ourselves of the truth of this statement, let us insert a series of tubes a, b, c, etc. in the upper side of the pipe EN. When the end N of the pipe is closed, we observe that the water will rise in all the tubes to the same level as that of the water in the tank; but as soon as water is permitted to flow through the outlet at N, this uniformity of level is disturbed and we find the water in the tube nearest the outlet to be so low as to be hardly visible, while from N toward E the water-level in the other tubes gradually rises along a line k, j', i', etc., called the *hydraulic gradient*, until the water in the tube a is very nearly at the same level as the water in the tank. As these tubes are in reality pressure-gages, the water in each tube will only rise to such a height that the weight of the water-column in the tube is sufficient to counterbalance the pressure at that part of the pipe.

The question now to be answered is, Why should not the water in the vertical tubes remain at the same level as that of the water in the tank when the outlet at N is open? The answer is, Because the water in motion meets a certain frictional resistance along the inside of the pipe, which it can only overcome by losing some of its pressure. A similar case would be that of a sled gliding over an icy surface; its frictional resistance is small until it meets a sandy spot, where the pull must be materially increased, because a large amount of power has to be devoted to overcoming the increased friction. The pressure and the pull that are used in both cases are transformed into heat.

102. Loss in Pressure.—The total loss in pressure in the pipe EN is indicated by the difference in the level of the water in the tube k and that in the tank, and if we suppose the length of the pipe to be 12 feet and the level of the water in the tank 27.5 feet above that in k, then the pressure per square inch at E will be 12 pounds. If we further assume the cross-sectional area of the upright tubes to be 1 square inch, then the weight in pounds of the column of water in each tube will correspond to the pressure per square inch at the base of the tube in the pipe. The tubes are supposed to be 1 foot apart, and the

reduction of pressure in each section or in each tube will therefore be $\frac{1}{12}$ of the whole, or 1 pound. The level in each consecutive tube will be 27.5 inches below that of the preceding one. We can see that the water in flowing from E to a has lost 1 pound in pressure, and that at a it has only a pressure of 11 pounds. This pound lost was consumed in overcoming the friction in section Ea. When we proceed to the tube f, we find that the pressure has decreased by 6 pounds, and that a pressure of only 6 pounds remains for forcing the water through the rest of the pipe. The excess of pressure at a over that at b corresponds to the difference of level at a' and b', and this is the

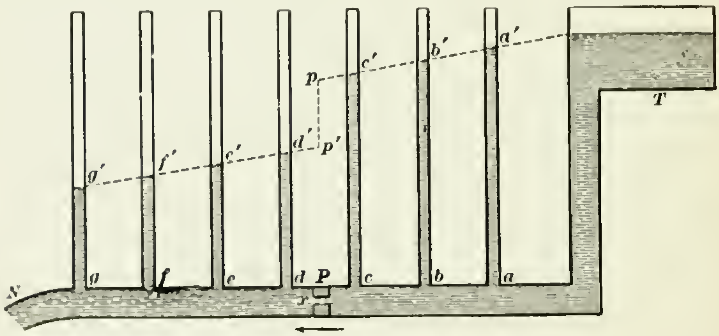

FIG. 18.

pressure that is needed to propel the water through that section. The force which causes the water to flow through the whole pipe is that due to the difference in level between the water in the tank and at N, and may be called the *watermotive force.*

The loss in pressure which takes place in the various sections $a\,b$, $b\,c$, etc. is uniform so long as the cross-sectional area of the pipe remains the same and the sections are of the same length, but when a resistance is interposed in the pipe, the fall of pressure will be more sudden. This is seen in Fig. 18, where a plug P is inserted in the pipe. As there is only a small aperture x in this plug, through which the water can flow, it necessarily limits the *whole* flow and reduces its rate; but the loss in pressure will be less than the reduction in flow. We see that the pressure suffers little reduction in the tubes a, b, c until

the plug is reached, when the pressure falls very suddenly along the line $p p'$, the fall being caused by the friction to which the water is exposed in passing through the plug. After leaving p', the pressure again falls gradually along a line parallel to $a' p$.

103. The E. M. F. in an Electric Circuit.—We are now in a position to more easily comprehend the action of an E. M. F. in an electric circuit. In Fig. 19, B represents a voltaic battery with the negative plate connected directly to the ground at E, and the positive plate to a long conductor $A L$, which is also connected to the ground at E'. The ground is here used as a return-conductor, as is the custom in telegraphy. It has been found that, if the ground-return

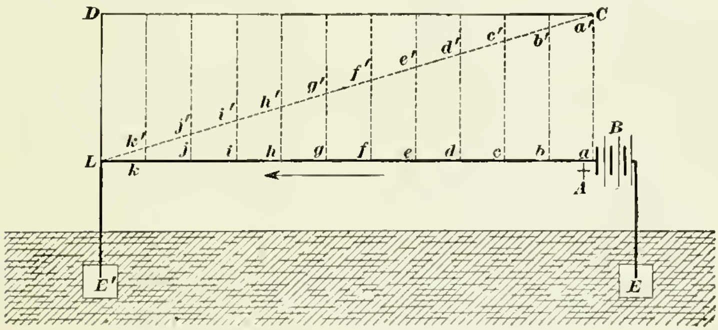

FIG. 19.

circuit is properly made, it practically makes no difference, as far as the resistance is concerned, whether it be 1 mile or 100 miles long. This is because of the large cross-sectional area which the ground offers to the current. But it is important that the plates E and E', which are usually made of iron or copper, should be buried so deep as to be surrounded at all times with a moist stratum, otherwise the resistance would be very high. In the present instance, the earth is used as a return-conductor, because it simplifies matters and makes the analogy between this and the previous example more apparent.

104. Function of the Battery.—The battery may, in this case, be regarded as a machine that raises the pressure or

potential of electricity from zero (or that of the earth) to a height that may be represented by the line $a a'$; or, in other words, the distance $a a'$ represents the available *electromotive force* of the battery. If the circuit is *opened*, or *broken*, between L and E', so that no current flows, then the difference of potential between the conductor and the earth is the same at all points along the conductor, and is represented by the distances between the line $C D$ and the conductor $A L$. Let it be assumed that the E. M. F. of the battery is 12 volts, and that the total resistance of the conductor $A L$, inclusive of the internal resistance of the battery, is 12 ohms. If the internal resistance of the battery be taken as 1 ohm, then that of each section $a b$, $b c$, etc. of the conductor will be 1 ohm, there being 11 sections, which, when added to the battery resistance, will make the total of 12 ohms.

Knowing the total E. M. F and the resistance, we can, by Ohm's law, find the current in amperes that will pass through the circuit. The formula $C = \frac{E}{R}$, in which $E = 12$ volts and $R = 12$ ohms, will give C the value of $\frac{12}{12} = 1$ ampere. The E. M. F. of the battery B will therefore send a direct current of 1 ampere through the whole conductor $A L$ down to the earth plate E', and, by means of the earth and the other plate, back again to the battery.

105. Current-Strength.—As it was found that the same amount of water was flowing in any part of the pipe in Fig. 17, so we have the same amount of electricity flowing through any point of the conductor. No matter how much the pressure may vary from point to point in the circuit, the current-strength in amperes remains *constant*. The current-strength is always the same in all parts of the circuit. This must be borne in mind, as the mistake is often made of supposing the current-strength to vary in the several parts of a circuit in accordance with the E. M. F. The total E. M. F. of a circuit determines once and for all the resulting current, and the latter remains unaltered as long as the determining factors, E. M. F. and resistance, remain

constant. The strength of the current will only change when either of these change, and then the flow will be altered at once in the *whole* circuit, not in parts of it. *When a change in current-strength occurs in a circuit, it does so uniformly, and not more in one part than in another.*

Let us now examine more closely into the alterations that the E. M. F. will undergo in the circuit illustrated in Fig. 19. We have already found that the resistance of 12 ohms will consume the entire E. M. F. of the battery; that is, the E. M. F. suffers a *loss*, or *drop*, of *electric potential* in the direction in which the current is flowing, and this difference of electric potential is caused by the flow of the electricity against the resistance of the conductor.

106. Drop of Potential.—The drop of potential between two points, say between a and b, is also found by means of Ohm's law; *the drop really represents the pressure or E. M. F. needed to send the current from* a *to* b. To find this E. M. F. we use the formula $E = C \times R$. The values of C and R were found to be 1 ampere and 1 ohm, respectively; E is therefore $1 \times 1 = 1$ volt; that is to say, there is a drop of 1 volt in each division $a\,b$, $b\,c$, $c\,d$, etc., and, as the resistance of the battery was 1 ohm, there is also a loss of 1 volt in the battery itself. If it is desired to find the loss of potential from a to d, the same formula is used, but one of the factors must now be changed; there are now three sections to consider, and therefore a resistance of 3 ohms. The formula will then read: $E = 1$ ampere $\times$ 3 ohms = 3 volts; hence, the drop or loss in the part $a\,d$ is 3 volts.

The diagram also shows the loss of E. M. F. in any part of the circuit by drawing a vertical line from the point in question on line $A\,L$ to line $C\,D$. Suppose, for instance, we wish to find the conditions at point g. The distance between the line $A\,L$ and $C\,D$ gives the total E. M. F. supplied to the conductor; of this E. M. F., the part above the line $C\,L$ is lost, and the part below the line—that is, the line $g\,g'$—corresponds to the amount of E. M. F. that remains for sending the current through the rest of the circuit.

107. Battery E. M. F.—In the preceding example we did not consider that loss of pressure which the current suffers in

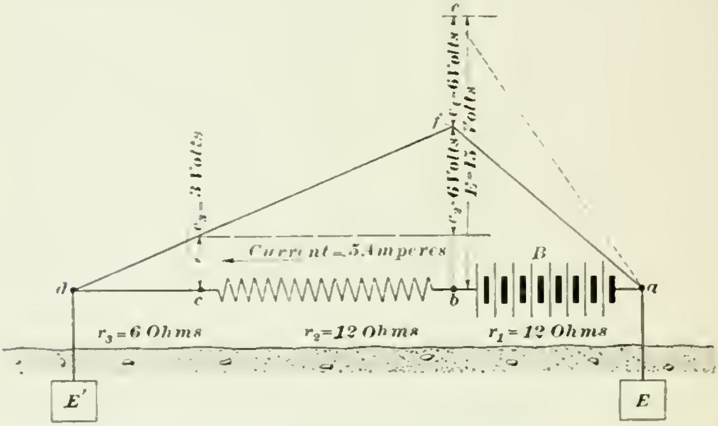

Fig. 20.

passing through the battery, but, as this is a point of some importance, it will now be considered more fully and illustrated by means of Figs. 20, 21, and 22.

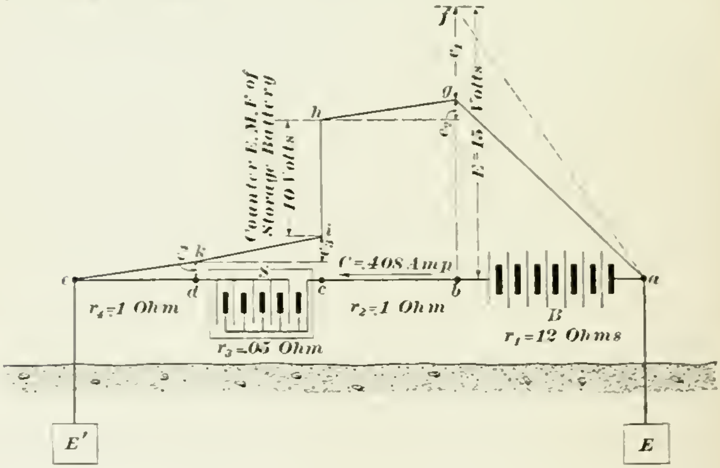

Fig. 21.

The calculation of the loss of E. M. F. between any two points is simple so long as the resistance of the circuit is

uniform throughout its length. When the circuit is made up of parts with differing resistances, then more care is required to determine the real loss or drop. A circuit of this character is shown in Fig. 20. The entire circuit is divided into three parts: *a b* containing the battery of 15 volts E. M. F. and 12 ohms resistance, a resistance coil *b c* of 12 ohms resistance, and a conductor *c d* of 6 ohms resistance. These three resistances are designated by the letters r_1, r_2, and r_3, respectively; the

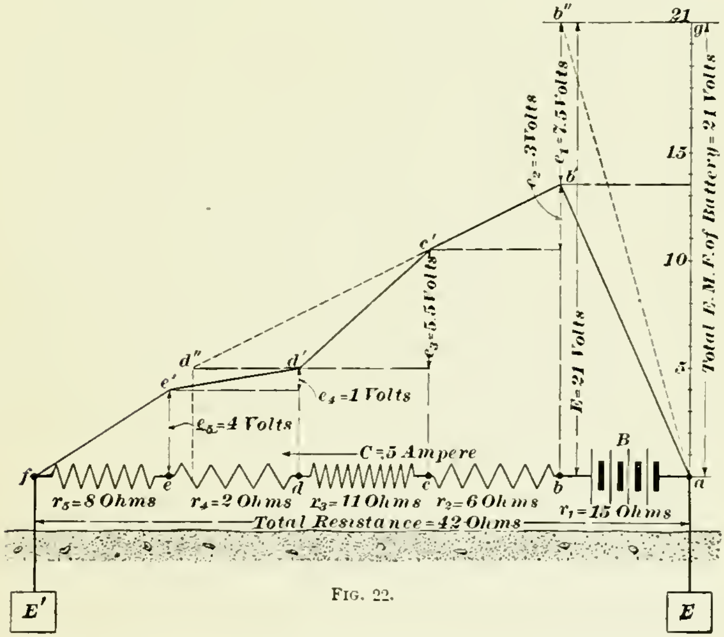

FIG. 22.

circuit is completed through the ground by means of the plates E and E', and this resistance may therefore be ignored.

The entire E. M. F. of the battery is represented by the line *b e*, and the drop of potential in the external circuit is supposed to take place along the line *f d*. Suppose it is desirable to find the loss of E. M. F. in each of the three divisions *a b*, *b c*, *c d*. Before this can be done, the current-strength of the circuit must be found. Here Ohm's law, $C = \frac{E}{R}$, is utilized; $E = 15$, and

$R = r_1 + r_2 + r_3 = 12 + 12 + 6 = 30$ ohms; therefore,
$C = \frac{15}{30} = .5$ ampere.

When the battery B is arranged as in the present instance, the cells are in series, as shown in Fig. 14 (b) and explained in Art. **98.** The nature of this combination will be made clear later on; for the present it will be sufficient to know that the pressure of each cell is added to that of the preceding one until finally the pressure reaches the value of 15 volts, as indicated by the line $b\,e$. The line $a\,e$ would show the increasing pressure of the battery as we approach the terminal b, but, as the battery has a resistance of 12 ohms, evidently a portion of the pressure must be lost before the current has traversed the whole battery. The latter has therefore to be treated as the rest of the circuit, and the drop that takes place in the battery calculated before we can know what the E. M. F. in the external circuit will be.

The drop is found by the equation $E = C \times R$; since C is a constant all through the circuit, it is necessary to change R only, and in each case to substitute for R the values of r_1, r_2, or r_3, as the case may be, in order to find the various drops e_1, e_2, and e_3.

First we have the battery itself, where $r_1 = 12$ ohms; therefore, $e_1 = C \times r_1 = .5 \times 12 = 6$ volts. The loss of voltage or drop that the current undergoes in passing through the battery is therefore 6 volts. Let us consider this point a moment, as it is necessary to be perfectly sure about this important part of the circuit. It was stated that the E. M. F. of the battery was 15 volts, and one would naturally suppose that this pressure would remain constant no matter what took place in the rest of the circuit. But we see now that this E. M. F. is 15 volts *only* when the battery is at rest, that is, when no current is flowing. As soon as the circuit is closed, the battery suffers like the rest of the circuit from the effects of resistance, and by reason of its resistance of 12 ohms, its E. M. F. of 15 volts is reduced to $15 - 6 = 9$ volts; that is, when the current enters the resistance coil at point c, it has an E. M. F. of 9 volts only, and the line $a\,f$ will therefore indicate the pressure of the battery.

We now come to the resistance-coil $b\,c$; here $e_2 = C \times r_2$,

that is, $e_2 = .5 \times 12 = 6$ volts. The E. M. F. is now reduced by another drop of 6 volts, and 3 volts only remain. In the last division $c\,d$ we have finally a resistance $r_3 = 6$ ohms, and the drop e_3 will be $C \times r_3 = .5 \times 6 = 3$ volts, a pressure sufficient to send the current to the battery through the earth plates E' and E. The resistance and loss in the circuit is shown in the following table, giving the corresponding drop for the various resistances :

Resistance. Ohms.	Loss. Volts.	Current. Amperes.
$r_1 = 12$	$e_1 = 6$	$C = .5$
$r_2 = 12$	$e_2 = 6$	$C = .5$
$r_3 = 6$	$e_3 = 3$	$C = .5$
Total, $r = 30$	$E = 15$	$C = .5$

108. Counter E. M. F.—There is yet another combination possible, that of a counter electromotive force acting in opposition to the E. M. F. of a primary battery. We saw in Art. **87**, when storage-batteries were considered, that while being charged they set up a counter E. M. F. in opposition to the impressed E. M. F. of the primary battery. It is of importance to see how this affects a closed circuit. In Fig. 21 is shown a storage-battery S included in a circuit in which B is the primary battery. The E. M. F. of the latter is, as in the previous case, 15 volts, and its resistance 12 ohms ; it is connected to the storage-battery S by means of a conductor $b\,c$ of .1 ohm resistance. The counter E. M. F. of the battery S is 10 volts and its resistance .05 ohm ; it is connected to a conductor $d\,e$ of .1 ohm resistance, which conductor may be connected directly either to the terminal a of the primary battery or to the ground, as in Fig. 21.

The line $b\,f$ represents the total E. M. F. of the battery B ; but, for reasons given in Art. **107**, the pressure will not increase along the line $a\,f$, but along $a\,g$, the difference e_1 representing the loss of pressure suffered by the current while passing through the battery. Passing from b to c the pressure drops from g to h,

and at this point we meet the counter E. M. F. of the storage-battery S, which immediately causes a drop of 10 volts, as shown by the line $h\,i$. In passing through this battery another loss is caused by its resistance, which is shown by line $i\,k$. Finally, the current passes through the remaining part $d\,e$ in which the pressure falls from k to e.

The procedure for finding the current-strength and drop of E. M. F. is the same as in the previous example. First find the total resistance R by adding the resistances r_1, r_2, r_3, and r_4. R is therefore $12 + .1 + .05 + .1 = 12.25$ ohms. In this instance the effective E. M. F. is equal to the difference between that of the battery B and that of the storage-battery S; therefore, $E = 15 - 10 = 5$ volts. We have, then, $C = \frac{E}{R} = \frac{5}{12.25} = .408$ ampere. The various losses of E. M. F in parts $a\,b$, $b\,c$, $c\,d$, and $d\,e$ are as shown in the following table:

$$
\begin{aligned}
e_1 &= 12.0 \times .408 = 4.90 \text{ volts.} \\
e_2 &= .1 \times .408 = .04 \text{ volt.} \\
e_3 &= .05 \times .408 = .02 \text{ volt.} \\
e_4 &= .1 \times .408 = .04 \text{ volt.} \\
&\text{Total, } \quad 5.00 \text{ volts.}
\end{aligned}
$$

109. Resistance and E. M. F.—Figs. 20 and 21 are likely to give the student a wrong impression, if not studied in conjunction with the figures giving the loss of E. M. F. at the various points; otherwise it might appear as if the potential were always falling along a straight line from the beginning to the end of the circuit. This will be the case only when, as in Fig. 19, the circuit throughout is of the same resistance per unit length; when the resistance varies, the E. M. F. will also vary and depart from the line representing the gradient. In representing these variations of the E. M. F. by means of diagrams, it sometimes happens that the length of the different divisions may be increased and decreased in such a manner as to make the gradient of one division fall in line with that of the previous one. This was done intentionally in Fig. 20, in accordance

with the prevailing custom, for the purpose of obtaining a symmetrical figure. The student is warned against any false impressions he may receive in studying these diagrams, but to still further show the actual conditions in a circuit, Fig. 22 has been added. B is a primary battery of 21 volts and 15 ohms; it sends a current of .5 ampere through a series of resistances of 6, 11, 2, and 8 ohms; in all a resistance of 42 ohms. To avoid any accidental symmetry in the diagram, the line af has been divided into 5 equal parts, each of a different resistance. The loss or drop is marked above the beginning of each division as in the previous figures; thus, above b we find $e_1 = 7.5$ volts, which is the loss of pressure that the current suffers in passing through the battery. The line ag is divided into 21 parts, corresponding to the 21 volts, and the various losses are counted off on this line; for instance, in counting off the drop of 7.5 volts, we come to the point 13.5, and from this point is drawn a horizontal line intersecting the line $b\,b''$ at b'. The section $b\,c$ is now subject to the remaining E. M. F. of 13.5 volts, but here it again suffers a loss, and the pressure then falls to c', corresponding to a loss of 3 volts. In this manner the losses are recorded in varying heights until the point f is finally reached. The diagram as completed clearly shows that the E. M. F. drops more quickly in those parts of the circuit where the resistance is greatest; for instance, in the divisions $a\,b$ and $c\,d$, where the resistances are, respectively, 15 and 11 ohms, the fall of pressure is much more rapid than in division $d\,e$, where the resistance is only 2 ohms. *It is seen that the fall in potential between any two points in a circuit is absolutely proportional to the resistance between these two points.* In fact, by going around the circuit until we meet a point where the potential has fallen to one-half its original value, as at c, where the potential is 10.5 volts, we know that the current at that point has passed through half the total resistance. At c, for example, the current has passed through a resistance of 21 ohms, that is, one-half of the total 42 ohms. So, in the same way, if the potential has decreased one-quarter of its full value, it is a proof of the fact that the current has passed through one-quarter of the whole resistance; in short, the loss of potential that the current suffers in passing through

a given part of a circuit has the same relation to the total E. M. F as the resistance of said part has to the total resistance.

By changing the lengths of the various divisions so that the lengths are proportional to the resistances, it is possible to make all the gradients one common line, as in Figs. 19 and 20. This is attained as shown at d'', to which position d' has been shifted; evidently, the diagram is now just as correct as before, as d'' shows the same loss of potential as d', but it does not convey a correct idea of the actual conditions in the circuit. By shifting the other points either to the left or the right, *all* may eventually be made to lie along the line $f\,g$, showing what is apparently a uniform decrease in pressure at points equidistant along the circuit.

DERIVED CURRENTS.

110. Conductivity.—So far we have considered the flow of an electric current in a single conductor. It is evident that there may be circuits in which the current flows between two points through two or more conductors, and that the current at these points will divide, one part flowing in one conductor and the other part in the other conductor. To know beforehand how many amperes will flow in each conductor or branch is of some importance, and the application of Ohm's law to a combination of this character will now be shown. It will be necessary beforehand to make an explanation of the word *conductivity.* Various substances have been spoken of as good conductors, meaning that they offer little *resistance* to the passage of an electric current, or in other words, that they are of high *conductivity.* It is therefore evident that conductivity is the inverse of resistance, its reciprocal.

As the term *resistance* is that most frequently employed, the term *conductivity* is rather superfluous. In fact, there is no established unit of conductivity, the term being employed merely because it is convenient in a few calculations relating to divided circuits. For example, if the resistance of a circuit is 2 ohms, the conductivity is represented by its reciprocal $\frac{1}{2}$. If the resistance is increased to 4 ohms, the conductivity would be one-half as much as in the former case, or $\frac{1}{4}$.

The conductivity of any conductor is, therefore, unity divided by the resistance of the conductor; and, conversely, the resistance of any conductor is unity divided by the conductivity of that conductor.

NOTE.—In treating derived currents, only that part of the circuit will be considered which is divided into branches and in which each branch transmits part of the total current; the rest of the circuit is assumed to be closed through some electric source, as, for instance, a voltaic battery.

111. Derived Circuit of Two Branches.—Fig. 23 represents a derived circuit of two branches.

Let r_1 = resistance of branch a;
r_2 = resistance of branch b;
c_1 = current in a;
c_2 = current in b;
C = current in the main circuit.

Then, $$c_1 + c_2 = C.$$

When the current flows from a to b, if the resistance r_1 and r_2 are equal, the current will divide equally between the two branches. Thus, if a current of 2 amperes is flowing in the main circuit, 1 ampere will flow through each branch.

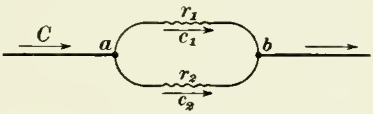

FIG. 23.

When the resistances are unequal, the current will divide inversely as the respective resistances of the two branches, or, since the conductivity is the reciprocal of the resistance, *the current will divide in proportion to their respective conductivities.*

In Fig. 23 the conductivities of the two branches are the reciprocals of the resistances r_1 and r_2; that is, $\frac{1}{r_1}$ and $\frac{1}{r_2}$, respectively. As the currents in the branches are proportional to their conductivities, we have

$$c_1 : c_2 :: \frac{1}{r_1} : \frac{1}{r_2}, \text{ or } \frac{c_1}{c_2} = \frac{r_2}{r_1}$$

Hence, $$c_1 = \frac{r_2}{r_1} \times c_2, \text{ and } c_2 = \frac{r_1}{r_2} \times c_1.$$

EXAMPLE.—Given, $C = 60$ amperes, $r_1 = 2$ ohms, $r_2 = 3$ ohms; find c_1 and c_2.

SOLUTION.—By formula, $c_1 = \frac{r_2}{r_1} \times c_2$, we find $c_1 = \frac{3}{2} \times c_2$. But $c_1 + c_2 = C = 60$, or $c_1 = 60 - c_2$.

Substituting for c_1 its value $60 - c_2$, we get $60 - c_2 = \frac{3\,c_2}{2}$.

Transposing, $5\,c_2 = 120$, or $c_2 = 24$ amperes. Ans.

$c_1 = 60 - 24 = 36$ amperes. Ans.

112. Joint Resistance.—It is evident that two conductors in parallel will transmit an electric current more readily than one conductor alone; that is, their *joint* conductivity is *greater* than that of either taken separately. This being the case, their resistances must follow the inverse law; viz., the *joint* resistance of the two conductors must be *less* than that of either taken separately.

If the individual resistances of two conductors are equal, their joint resistance when connected in parallel is one-half of the individual resistance of either.

Suppose a conductor $A\,B$, Fig. 24, is split longitudinally into two halves a and b. If $A\,B$ has a total resistance of 5 ohms between the points c and d, evidently the branches a and b must each have a resistance of 10 ohms, since they have only one-half of the cross-sectional area of $A\,B$. Thus, their joint resistance does *not* amount to $10 + 10 = 20$ ohms, but to $\frac{10}{2} = 5$ ohms only.

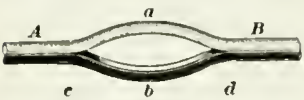

FIG. 24.

113. Between the points c and d, Fig. 22, there is a difference of potential. Suppose another conductor in shunt to be also connected to the terminals c and d; it would evidently be subject to an E. M. F., and what would be the result? Fig. 25 illustrates this combination, in which r_6 is a shunt of 11 ohms resistance. We know from the preceding example that each conductor would transmit one-half of the total current, or

.25 ampere. It is therefore clear that an active conductor can be "tapped" at various points, and part of the current taken through some outside device. The strength of this current depends on the difference of potential at the terminals of the shunt and on its resistance.

To avoid drawing false conclusions from the effect of the shunt in Fig. 25, it would be in order to ask the question, When the resistance of conductor cd is reduced to one-half of its original value by the addition of the shunt ckd, does not this reduction affect the current strength through the whole circuit? It does, because a decrease in resistance of one part of a circuit will decrease the total resistance. In the present case, it will increase the current strength of the circuit in Fig. 22 to .575 ampere, and will decrease the drop between c and d to 3.16 volts instead of the 5.5 volts previously existing.

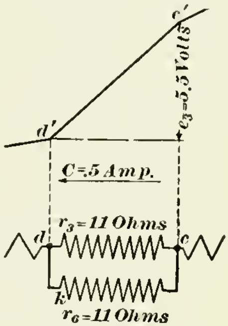

FIG. 25.

When the individual resistances of two conductors in parallel are *unequal*, the determination of their joint resistance when connected in parallel involves some calculation.

In Fig. 23, the conductivities of the branches are $\frac{1}{r_1}$ and $\frac{1}{r_2}$, respectively.

Let K = their joint conductivity;
R = their joint resistance.

Then,
$$K = \frac{1}{r_1} + \frac{1}{r_2} = \frac{r_1 + r_2}{r_1 r_2};$$

$$R = 1 \div \frac{r_1 + r_2}{r_1 r_2} = \frac{r_1 r_2}{r_1 + r_2}.$$

Rule.—*The joint resistance of two conductors in parallel is the quotient obtained by dividing the product of their individual resistances by the sum of their individual resistances.*

EXAMPLE.—In Fig. 23, given, $r_1 = 4$ ohms, $r_2 = 6$ ohms, and $C = 30$ amperes; find c_1 and c_2, and the joint resistance R of the branches from a to b.

SOLUTION.—Using the formulas from Art. **111**, we have

$$c_1 = \frac{r_2}{r_1} \times c_2 = \frac{6}{4} \times c_2,\ c_1 + c_2 = C = 30, \text{ and } c_1 = 30 - c_2.$$

Substituting for c_1 its value, $30 - c_2$, we get $30 - c_2 = \frac{6}{4} c_2$.

Reducing gives

$$10\, c_2 = 120, \text{ or } c_2 = 12 \text{ amperes. Ans.}$$

$$c_1 = 30 - 12 = 18 \text{ amperes. Ans.}$$

From the formula $R = \frac{r_1 r_2}{r_1 + r_2}$, we have

$$R = \frac{4 \times 6}{4 + 6} = \frac{24}{10} = 2.4 \text{ ohms. Ans.}$$

114. 1. *The joint resistance of three or more conductors in parallel is equal to the reciprocal of their joint conductivity.*

Fig. 26 represents a derived circuit of three branches. Let r_1, r_2, and r_3 = the individual resistances of the three branches, respectively; therefore, $\frac{1}{r_1}$, $\frac{1}{r_2}$, and $\frac{1}{r_3}$ represent the individual conductivities of the three branches, respectively. Their joint conductivity is

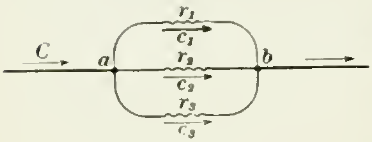

FIG. 26.

$$K = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} = \frac{r_2 r_3 + r_1 r_3 + r_1 r_2}{r_1 r_2 r_3}$$

Since the joint resistance is the reciprocal of the joint conductivity,

$$R = 1 \div \frac{r_2 r_3 + r_1 r_3 + r_1 r_2}{r_1 r_2 r_3} = \frac{r_1 r_2 r_3}{r_2 r_3 + r_1 r_3 + r_1 r_2},$$

which is the joint resistance of the three branches in parallel from a to b.

Example.—In Fig. 26, given, $r_1 = 5$ ohms, $r_2 = 10$ ohms, and $r_3 = 20$ ohms; find their joint resistance from a to b.

Solution.—The joint resistance is

$$R = \frac{r_1 r_2 r_3}{r_1 r_2 + r_1 r_3 + r_2 r_3} = \frac{5 \times 10 \times 20}{5 \times 10 + 5 \times 20 + 10 \times 20}$$

$$= \frac{5 \times 10 \times 20}{50 + 100 + 200} = \frac{1{,}000}{350} = 2.857 \text{ ohms. Ans.}$$

2. To find the E. M. F. in a derived circuit when the current and resistance in each branch are known.

Rule.—*In any derived circuit, the difference of potential between where the branches divide and where they unite is equal to the product of the sum of the currents in the separate branches by their joint resistance in parallel.*

Example.—If the currents in the three branches, Fig. 26, are 16, 8, and 4 amperes, respectively, and the joint resistance from a to b is 2.857 ohms, what is the difference of potential between a and b?

Solution.—The sum of the currents in the branches is $16 + 8 + 4 = 28$, and $28 \times 2.857 = 80$ volts. Ans.

3. To find the individual currents in any branch of a derived circuit.

Rule.—*Determine the difference of potential between where the branches divide and where they unite, and divide the result by the resistance of the branch in question.*

Example.—In Fig. 26, assume that the difference of potential between a and b is 80 volts, and that the individual resistances of the three branches are, respectively, 5, 10, and 20 ohms. What is the current in each branch?

Solution.—The current in the first branch is $\frac{80}{5} = 16$ amperes; in the second, $\frac{80}{10} = 8$ amperes; and in the third, $\frac{80}{20} = 4$ amperes. Ans.

4. To find the individual resistance of any branch of a derived circuit.

Rule.—*Determine the difference of potential between where the branches divide and where they unite, and divide the result by the current in the branch in question.*

EXAMPLE.—In Fig. 26, assume the difference of potential between *a* and *b* to be 80 volts, and the currents in the individual branches to be 16, 8, and 4 amperes, respectively. What is the resistance of each branch?

SOLUTION.—The resistance of the first branch is $\frac{80}{16} = 5$ ohms; of the second, $\frac{80}{8} = 10$ ohms; and of the third, $\frac{80}{4} = 20$ ohms. Ans.

ARRANGEMENT OF CELLS.

115. Main Principles.—A voltaic cell, as usually constructed, is a source of electromotive force, the properties of which are constant. In other words, whenever a single cell is set in action, its E. M. F. and resistance are constant as long as the original conditions remain unaltered. If this E. M. F. is not of the value desired for the purpose in view, a change must be effected either in the cell itself or external to it. The first method is rarely used except in the various plunge-batteries, where the strength of the current may be regulated by changing the internal resistance of the battery. But, as a rule, this internal resistance is a constant in the average cell. In some cells it may be excessively large, owing to the resistance of the electrolyte, the relative resistance of the liquids ordinarily used as electrolytes being from one million to twenty million times that of the metals. In liquids, as in all conductors, the resistance increases as the length of the circuit increases, and diminishes as its sectional area increases. Consequently, the internal resistance of a simple voltaic cell is reduced by decreasing the distance between the two plates, or elements, or by increasing their active surfaces. In most cells these points have already been taken advantage of, and no alteration can be made in the cell itself, and, as the E. M. F. cannot be altered, the change, if necessary, must be made external to the cell. The only way left to change the E. M. F. and resistance of a battery is, therefore, either to place a resistance in the circuit, to combine a number of cells in a manner most suitable for the purpose in view, or to use both of these means in conjunction.

Before discussing the various methods of arranging the cells, it will be of advantage to examine into the effects produced by altering the *size* of a cell, as the statement is often made that a large cell has a higher E. M. F. than a small one.

116. The Size of a Cell.—For the sake of an easier understanding, we will again use an analogy from hydraulics. Let *A* and *B*, Fig. 27, be two cylinders in which the pistons *b* and *c* move freely. The cylinders are in communication with each other by means of the tube *a*, and the latter is provided with a pressure-gage *g*. It is supposed that the pistons *b* and *c* have a surface area of 12 and 120 square inches, respectively. It is further supposed that the weight of either piston

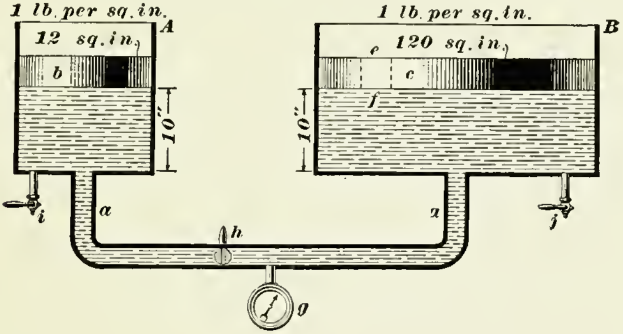

FIG. 27.

is such that any portion of them, such as *ef*, in which the base is 1 square inch, will weigh exactly 1 pound. The pistons *b* and *c* will then weigh 12 and 120 pounds, respectively, and, if both cylinder and tube are filled with water, there will be a total pressure of 12 pounds at the bottom of cylinder *A*, and 120 pounds at the bottom of cylinder *B*. The weight of the water is not considered. There will therefore be a pressure of 1 pound per square inch on the bottom of either cylinder and also in the tube, the cross-sectional area of the latter being 1 square inch. It is now evident that an increase in diameter of either of the pistons will increase the total pressure on the bottom of either cylinder, but will not affect the pressure per square inch; the gage will register 1 pound at all times, and

the pistons will be perfectly balanced. Of course the *volume* of water contained in either cylinder will vary independently of the pressure. Thus, by closing the valve h, preventing com-

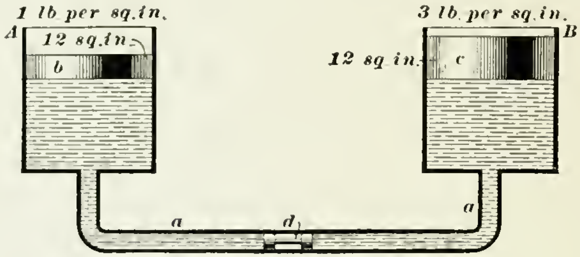

FIG. 28.

munication between the cylinders, the cylinder A might be emptied through the valve i and would give 120 cubic inches of water, while B, through valve j, would supply 1,200 cubic inches.

As long as the weight per square inch of either piston is the same, there will be no motion, but if there is an excess in pressure on one piston, as in Fig. 28, then the conditions are no longer the same. Here the pressure per square inch exerted by piston c is 3 pounds, while that exerted by b is 1 pound, as before. If a piston d of a cross-sectional area of 1 square inch be inserted in the tube a, there will be an excess of pressure amounting to 2 pounds on its right side, and it will move to the left; in other words, there will be a current of water flowing towards the left.

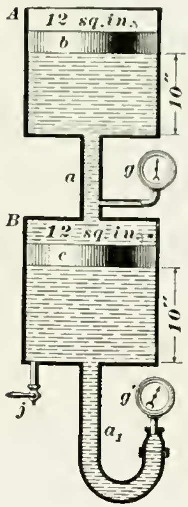

FIG. 29.

117. Suppose the cylinders to be arranged as in Fig. 29, one above the other. The areas of both pistons are the same, 12 square inches, and the weight per inch of area 1 pound, as before; the gage g will therefore show a pressure of 1 pound per square inch. Evidently the pressure exerted by the piston c is greater, as

in addition to the 12 pounds of its own, it has received on its upper surface a pressure of 12 pounds, through the tube *a* from the piston *b*. The total pressure exerted by *c*, remembering that the water is considered as having no weight, will, therefore, be $12 + 12 = 24$ pounds, that is, 2 pounds per square inch, which pressure will be indicated by the gage g'. Should the cylinder *B* be emptied through the valve *j*, it will deliver the same quantity of water as cylinder *A*, 120 cubic inches; but it will be delivered under double the pressure. It is clear that, by the addition of more cylinders and pistons connected in the same manner, the pressure will be increased 1 pound per square inch for each cylinder added, but that, on the other hand, the quantity of water delivered will be the same as that of one cylinder.

118. In an arrangement such as shown in Fig. 30, in which all the cylinders *A* communicate by means of tubes *a*,

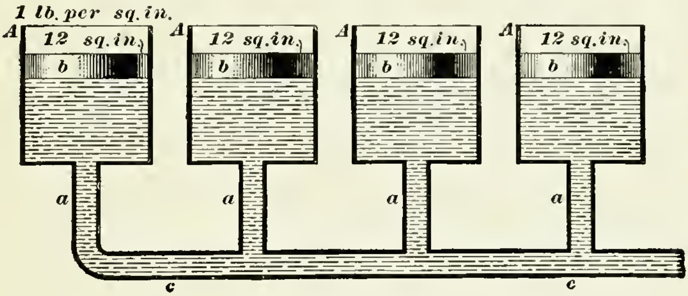

FIG. 30.

with a common tube *c*, any increase in the number of cylinders will not increase the pressure in the tube *c*. Thus, if the pressure exerted by each of the pistons *b* is 1 pound per square inch, the pressure in the tube will be the same no matter how many cylinders are added. But, though the pressure is not increased, the quantity of water that may be delivered will of course be greater as the number of cylinders increases.

The cylinders in Fig. 29 are placed in *series* so as to add their pressures, while the cylinders in Fig. 30 are arranged in *parallel*, so as to add the volumes delivered. The general

effects produced by the various combinations of voltaic cells on the volume and pressure of an electric current are exactly similar to those just described, and by using this analogy of pressure and flow of water, it is easier to understand the action in the voltaic cell.

119. Cells in Parallel.—We have seen that in the simple voltaic cell, as shown in Fig. 31 (*a*), zinc was the active element. It may simplify matters by supposing that each square inch of its surface would be able to deliver a certain quantity of electricity under a given pressure. For instance, let each square inch supply a current of .1 ampere at a pressure of 1 volt. Considered in this manner, however small or large the zinc plate may be, the pressure would remain at 1 volt; but the amount of electricity delivered would increase or decrease as the plate increased or decreased in size. For each square inch added, we would have another .1 ampere. This

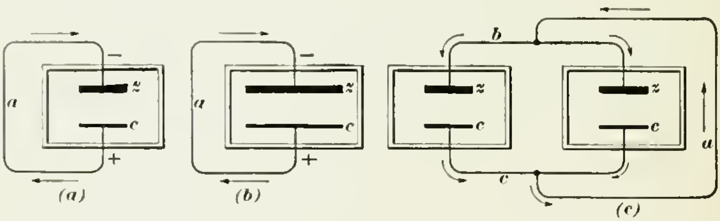

FIG. 31.

case is exactly parallel to that illustrated by means of Fig. 27. We saw there that an increase in the diameter of the pistons did not affect the pressure per square inch, but only the volume of water delivered.

To increase the strength of the current in the voltaic cell, Fig. 31 (*a*). we may proceed in two ways, either as in Fig. 31 (*b*), by increasing the active area, or as in Fig. 31 (*c*), by adding one or more elements of the same size. For instance, if the current-strength of the cell in Fig. 31 (*a*) is to be doubled, we may either, as in Fig. 31 (*b*), double the size of the plates, or, as in Fig. 31 (*c*), add another cell of the same size and connect them in parallel. In the latter figure, the two zinc plates *z* and copper

plates c are connected by means of the wires b and c, and thus constitute, practically, one plate of zinc and one of copper, but both of doubled area. The wire a unites the two combined elements in a manner similar to that of Figs. 31 (a) and 31 (b). In the arrangement shown in Fig. 31 (c), the cells are joined in *parallel*, and correspond to the combination illustrated in Fig. 30.

120. Suppose the cell in Fig. 31 (a) has an E. M. F. of 1.1 volts and an internal resistance of .6 ohm, the current strength would be $\frac{1.1}{.6} = 1.8$ amperes.

In Fig. 31 (c), we have two similar cells coupled in parallel, and we might say that the current of two cells is $1.8 \times 2 = 3.6$ amperes. But it is customary to consider the cells as a derived circuit, and treat their resistances accordingly, since it simplifies the calculations when it comes to more complex combinations. In the present case there are two cells of the same resistance; their joint resistance will therefore be one-half of their separate resistances, as shown in Art. **112.**

If we call the internal resistance r and the number of cells in parallel n, their joint resistance is $\frac{r}{n}$. Thus, we find the joint resistance of the cells in Fig. 31 (c) to be $\frac{.6}{2} = .3$. Therefore, $C = \frac{1.1}{.3} = 3.6$ amperes, as before. Should there be six similar cells in parallel, we would find their resistance $\frac{.6}{6} = .1$ ohm, and then $C = \frac{1.1}{.1} = 11$ amperes.

Looking upon Fig. 31 (c) as a derived circuit, it is clear that the current in passing through each cell has to pass through the fluid between the plates z and c, and that the resistance of this fluid column will depend on its cross-sectional area. When the cells are, as in this case, placed in parallel, it is evident that the area of the fluid conductor is doubled and the resistance thereby halved.

121. In Fig. 32 the cells of Figs. 31 (a) and 31 (b) are joined in the manner indicated, which corresponds to the two

cylinders in Fig. 27. In either case the result is the same; that is, there will be no current, because the pressures of E. M. F. in the cells are the same and acting in opposition to each other. That one cell is much larger than the other does not alter the conditions. The arrows indicate the direction in which the electromotive forces tend to act.

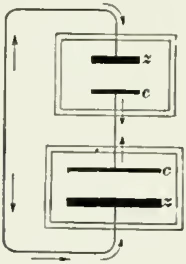

FIG. 32.

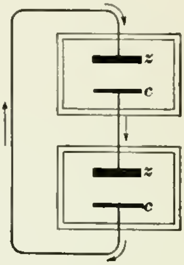

FIG. 33.

122. Cells in Series.—In Fig. 33 we have a combination corresponding to that shown in Fig. 29, two cells placed in series. *Not only are the pressures of the cells united, but their resistances also.* Since the current has to go through both resistances one after the other, the length of the fluid column is doubled and consequently the resistance also.

Using the same value for r and n as in Art. **120,** let

E = E. M. F. of each cell;
R_s = total resistance of the cells in series;
E_s = total E. M. F. of the cells in series.

Then,
$$R_s = n \times r;$$
$$E_s = n \times E.$$

Let r be .6 ohm, as before, and E, 1.1 volts, and we have

$$E_s = n \times E = 2 \times 1.1 = 2.2 \text{ volts},$$
and
$$R_s = n \times r = 2 \times .6 = 1.2 \text{ ohms}.$$

The current-strength C will therefore be:

$$\frac{E}{R} = \frac{2.2}{1.2} = 1.8 \text{ amperes},$$

or the same as that of 1 cell. This is at first glance surprising,

but an examination of the formula used for finding C will show the reason for it. Since

$$C = \frac{E_s}{R_s} = \frac{n\,E}{n\,r} = \frac{E}{r},$$

and n stands for the number of cells in series, it is evident that, by increasing n, both the dividend and the divisor increase in the same proportion, and that the quotient will therefore remain unaltered.

123. Cells Connected With an External Resistance. We are now ready to enter into an examination of the more complex combinations of voltaic cells with an external resistance, and the way R affects the total E. M. F. and the current-strength. To make these effects more clearly understood, a series of diagrams has been devised which will assist the student very materially in grasping the subject.

It has already been shown, by means of Figs. 19 and 20, that, after the electric current has left the battery and entered the

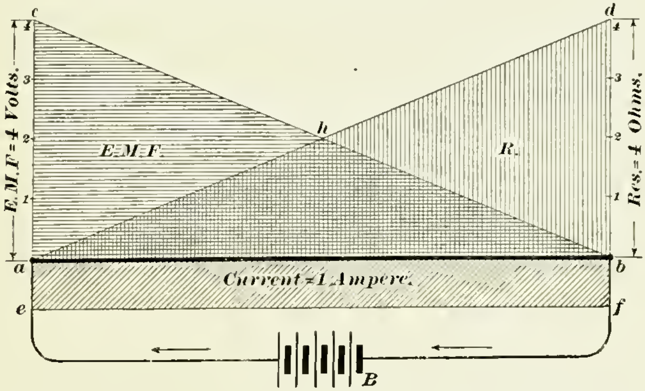

Fig. 34.

external circuit, the E. M. F. of the current is constantly decreasing, in some parts of the circuit more rapidly than in others, and these variations in E. M. F. were shown by various gradients. The resistance of a conductor varies with its length, that is, the longer the conductor, the higher the resistance; consequently, the resistance along a circuit will rise as the E. M. F. falls. Fig. 34 will show this effect more clearly. It gives in a

diagrammatic form the relation between the E. M. F., the current-strength, and the resistance of a conductor. In the present instance, the resistance of the battery B has been left out of consideration and only that of the conductor $a\,b$ is considered. The available E. M. F. of the battery is 4 volts, and the resistance of the conductor 4 ohms. If we now select some arbitrary length for 1 volt, and measure four of these along the line $a\,c$, we reach the point c corresponding to the E. M. F.; and, by connecting c with point b, the triangle $a\,b\,c$ will show the E. M. F. along the line. In the same manner the resistance of 4 ohms is laid off along the line $b\,d$, and the points d and a connected. The triangle $a\,b\,d$ will then represent the resistance

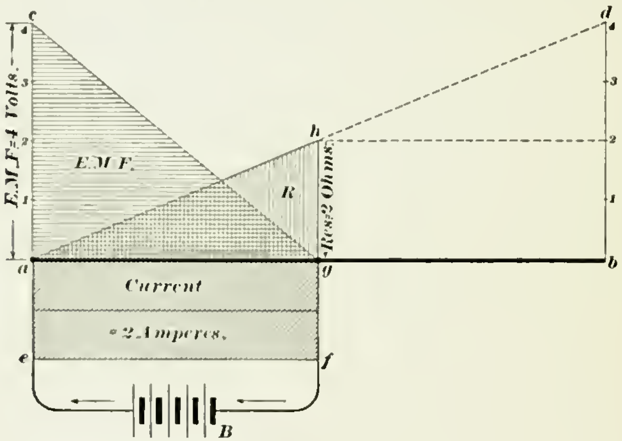

FIG. 35.

of the conductor, and if we let the distance $a\,e$ represent the current-strength of 1 ampere, and through e draw a line parallel to $a\,b$, the rectangle $a\,e\,f\,b$ will correspond to the volume of the current, which is, in this instance, 1 ampere.

We now see that the E. M. F. is at its maximum at c, and that from c it gradually decreases until it reaches the point h, which is just over the middle point of the conductor, where the E. M. F. has diminished to one-half of its original value. From here it continues to fall till the point b is reached, where the pressure is zero. Simultaneously with the fall of E. M. F., the

resistance, starting from a, has been gradually rising until at h it has attained one-half of its maximum value, and at d its full value of 4 ohms. *The strength of the current has, of course, been constant throughout the whole length of the conductor.*

124. Disconnecting the Battery.—It will be interesting at this point to watch the effect of disconnecting the battery from the terminal b and make a connection with some other part of the conductor. A change of this character has been made in Fig. 35. One terminal of the battery has been moved to g, $a\,g$ being one-half the length of the whole conductor. If a vertical line be drawn through the point g, it intersects the line $a\,d$ at point h, which shows the resistance to be 2 ohms.

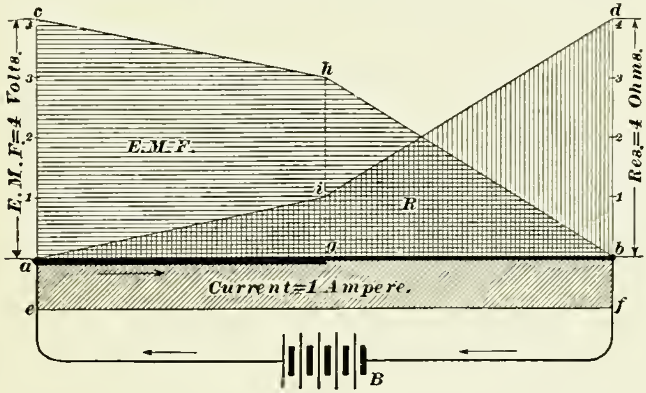

Fig. 36.

The E. M. F. is indicated by the triangle $a\,c\,g$, and the current by the rectangle $a\,c\,f\,g$. It is thus seen that the current-strength has increased to 2 amperes, because the resistance has been halved, and, therefore, $C = \frac{4}{2} = 2$ amperes. On moving the battery connection still further towards the left, the resistance would decrease, the current in amperes increase, and the E. M. F. remain constant. This is on the supposition that the available pressure of the battery remains *constant*, which would not, however, be the case under the conditions here assumed.

125. Effect of Resistance.—We will now go a step further, and in the next diagram, Fig. 36, how the effect of a

resistance that is not uniform. The resistance of the part $a\ g$ of the conductor is 1 ohm, as shown by the line $g\ i$; the remainder of the conductor has a resistance of 3 ohms, that of the entire conductor being 4 ohms. The E. M. F. is, as before, 4 volts, which at point h has fallen to 3 volts, and between h and b it falls more rapidly to zero. The current of 1 ampere has again remained constant throughout the whole length of the conductor.

126. Resistance of Battery.—So far the resistance of the battery has been left out of consideration, but as any changes

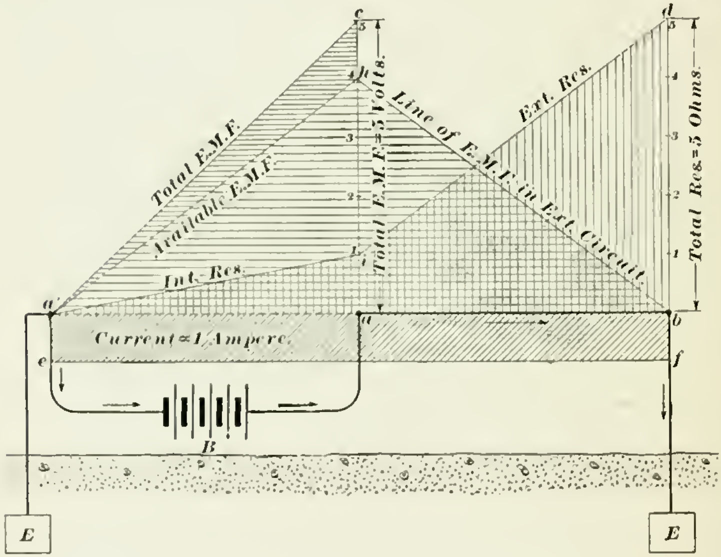

FIG. 37.

that take place in the external circuit also influence the battery in one way or another, it will be necessary to also include the latter in the diagrams.

In Fig. 37 is shown a battery of 5 cells in series, each cell being of 1 volt E. M. F and .2 ohm internal resistance. The total E. M. F. is $5 \times 1 = 5$ volts, and the total internal resistance is $5 \times .2 = 1$ ohm. The external resistance is 4 ohms, which, together with the 1 ohm of the battery, makes the total resistance 5 ohms. The current-strength C is then $\frac{5}{5} = 1$

ampere. The loss of E. M. F. in the battery will be $C \times r = 1 \times 1 = 1$ volt. These figures are represented in the diagram in the following manner: The line $a\,b$ represents, as before, the external circuit, and $a\,a'$ the internal circuit through the battery. The total E. M. F. is $a\,c$, and corresponds to 5 volts. We see that this E. M. F. is gradually rising from the point a', each cell adding its E. M. F. until the fifth cell brings the pressure up to c. At the same time the resistance of the battery has also been increasing, beginning at a', the five cells, of .2 ohm resistance each, making a total of 1 ohm, as shown at $a\,i$. To this is added, at point i, the resistance of the external circuit, 4 ohms, making a total resistance of 5 ohms, as indicated by the line $b\,d$. Returning to the E. M. F. of the battery, it is observed that 1 volt has been lost in overcoming the resistance of the battery; this loss is represented by the line $c\,h$, and the triangle $a'\,c\,h$ shows the distribution of this loss. Hence, the available E. M. F. is only 4 volts, as indicated by the line $h\,a$. As soon as the current leaves the battery at a, the pressure begins to fall, and continues to decrease till the point b is reached, where the current again enters the battery. The current-strength is indicated by the line $a'\,e$ or $b\,f$, and is constant throughout the circuit. The circuit is supposed to be completed through the earth.

127. In order to still more condense the diagram shown in Fig. 37, it has been transformed to the form shown in Fig. 38. Here that part of the diagram which, in Fig. 37, was situated at the left of the line $c\,a$ has, so to say, been folded over and laid on that part of the diagram which lies at the right of line $c\,a$. As the arrangement of cells will be treated by diagrams drawn in this form, a few additional explanations will not be out of place.

The line $a\,c$ represents the total E. M. F. of the battery, 5 volts; the line $c\,h$, the loss of E. M. F. taking place in the battery itself. The triangle $a\,h\,b$, therefore, indicates the available E. M. F. The battery is connected to the external circuit $a\,b$ at the terminals a and b, and we have, as before, the fall of E. M. F. in the external circuit along the line $h\,b$. The rise of E. M. F. in the battery can also be observed by proceeding

from b along the line $b\,c$. The more heavily shaded triangle $b\,c\,h$ represents the E. M. F. lost in the battery. The battery resistance that causes this loss is shown by means of the more heavily shaded triangle $a\,d\,i$, $d\,i$ being 1 ohm; while the triangle $a\,b\,i$ represents the resistance of the external circuit. The current-

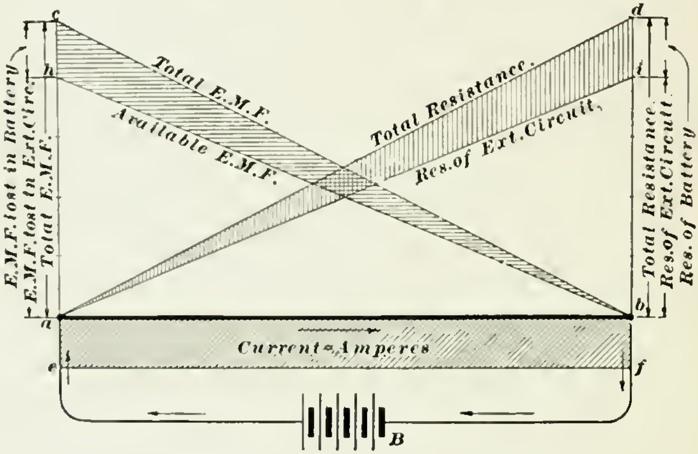

FIG. 38.

strength is, as before, indicated by the distance of the line $c\,f$ from $a\,b$, being proportional to the length of the line $a\,e$ or $b\,f$.

128. Fundamental Formula.—We are now prepared to study the arrangement of cells most suitable for the purpose for which they are to be used. In the following formula

C = current in the circuit;
r = internal resistance of a cell;
R = external resistance;
E = total E. M. F. of the whole battery;
e = E. M. F. of one cell;
s = number of cells in series;
p = number of cells in parallel;
r' = total internal resistance;
n = total number of cells;
V = terminal or available E. M. F of the battery;
W = power in watts.

As already mentioned, the total E. M. F. of a battery depends on the number of cells in series; therefore, $E = s \times e$.

The total internal resistance depends on whether the cells are in series or parallel, or in a combination of both series and parallel.

If all the cells are placed in series, the internal resistance $r' = s \times r$; if placed in parallel, $r' = \frac{r}{p}$.

When the cells are partly in series and partly in parallel,

$$r' = \frac{s \times r}{p}.$$

From this we will find that the total current which the battery is capable of sending through the external resistance R is found, in *parallel series*, as follows:

$$C = \frac{E}{r' + R}.$$

Therefore, $$C = \frac{s\,e}{\frac{s \times r}{p} + R}. \qquad (a)$$

This formula can be used for any number of combinations of cells in *parallel series*, or for a single row of cells, either in *series* or *parallel*.

In using the formula for cells in *series*, it will appear in this form:

$$C = \frac{s\,e}{\frac{s\,r}{1} + R}.$$

Therefore, $$C = \frac{s\,e}{s\,r + R}. \qquad (b)$$

For cells in *parallel* the following formula will be evolved:

$$C = \frac{1 \times e}{\frac{1 \times r}{p} + R}.$$

Therefore, $$C = \frac{e}{\frac{r}{p} + R}. \qquad (c)$$

129. Effect of Combining Cells.—Let us, by means of a few examples, see the effect of combining the same number of cells (1) in *series*, (2) in *parallel*, and (3) in *parallel series.*

Suppose it is desired to send a current through an external resistance of 5 ohms by means of 12 Daniell cells, each of which has an internal resistance of .6 ohm and an E. M. F. of 1.1 volts.

Then,

$$e = 1.1;$$
$$r = .6;$$
$$R = 5.0;$$
$$n = 12.0;$$
$$C \text{ is unknown.}$$

1. Placing all the cells in *series*, we use formula (b),

$$C = \frac{s\,e}{s\,r + R}.$$

Therefore, $C = \dfrac{12 \times 1.1}{12 \times .6 + 5} = \dfrac{13.2}{12.2} = 1.082.$

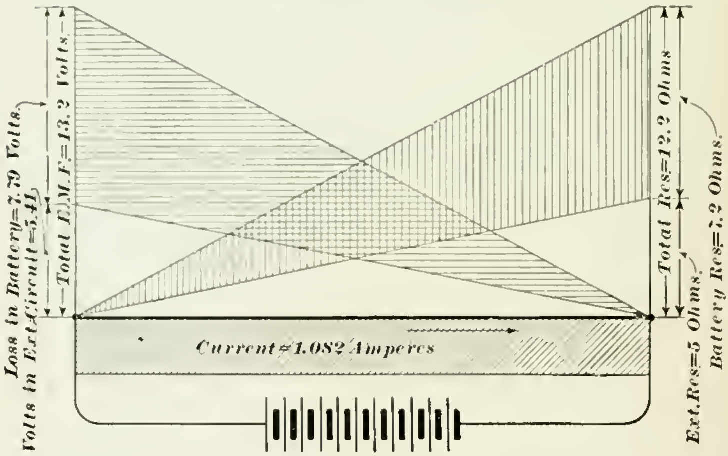

FIG. 39.

The resistance r' of the whole battery $= 12 \times .6 = 7.2$ ohms.

	Volts.
E. M. F. lost in battery $= C \times r' = 1.082 \times 7.2 =$	7.79
Volts lost in external circuit $C \times R = 1.082 \times 5 =$	5.41
The total E. M. F. = the sum =	13.20

The above arrangement is shown in Fig. 39.

2. All the cells are placed in *parallel*. Using formula (c), we find

$$C = \frac{e}{\frac{r}{p} + R} = \frac{1.1}{\frac{.6}{12} + 5} = \frac{1.1}{5.05} = .21782.$$

Resistance of the whole battery $r' = \frac{r}{p} = \frac{.6}{12} = .05$ ohm.

	Volts.
E. M. F. lost in battery $= C \times r' = .217 \times .05 =$	.01
E. M. F. lost in external circuit $= C \times R = .217 \times 5 =$	1.09
Total E. M. F. = the sum =	1.10

Fig. 40 shows the above arrangement.

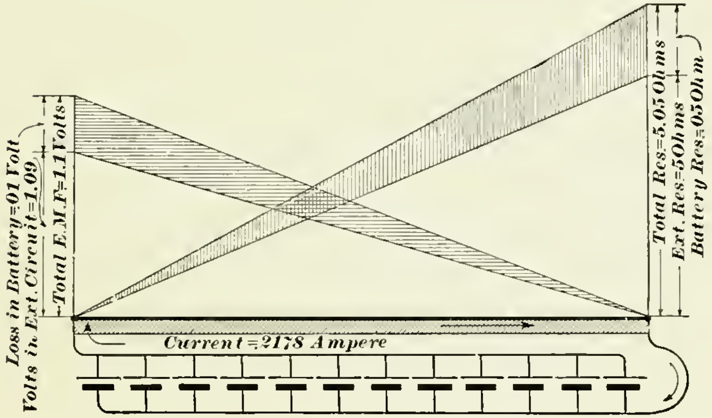

FIG. 40.

3. Let the cells now be placed 4 in *series* and 3 in *parallel*. Then, $s = 4$, $p = 3$, and formula (a) now gives

$$C = \frac{s\,e}{\frac{s \times r}{p} + R} = \frac{4 \times 1.1}{\frac{4 \times .6}{3} + 5} = \frac{4.4}{5.8} = .7586 \text{ ampere.}$$

Resistance of the whole battery $r' = \frac{s \times r}{p} =$ .8 ohm.
Resistance of the external circuit $R =$ 5.0 ohms.
Total resistance = 5.8 ohms.

E. M. F. lost in battery $= .8 \times .7586 =$ .61 volts, nearly

E. M. F. lost in external circuit $= 5 \times .7586 =$ 3.79 volts.

Total E. M. F. = the sum = 4.40 volts.

The above arrangement is illustrated by means of Fig. 41.

With the external resistance of 5 ohms, we find that the greatest pressure is furnished to the external circuit by the first combination, as shown in Fig. 39, and the smallest pressure by the arrangement in parallel, as shown in Fig. 40. The loss of E. M. F. in the battery was much smaller in Fig. 40 than in

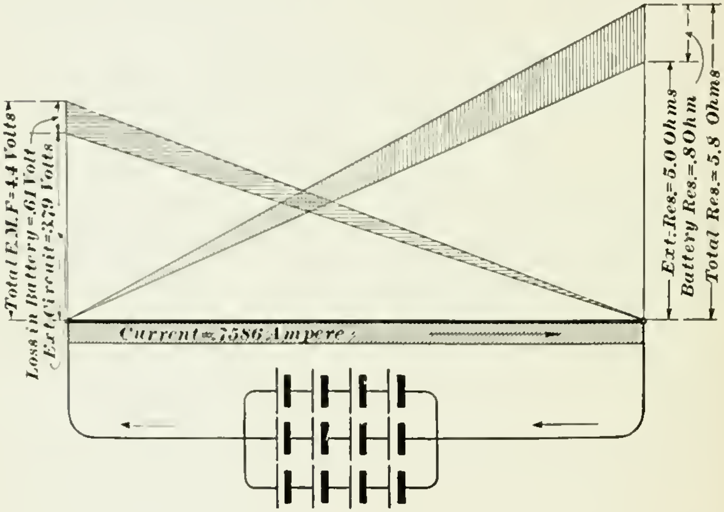

FIG. 41.

Fig. 39, and yet a smaller pressure was delivered to the external circuit, because the total pressure was only that of 1 cell. We also note that the battery resistance in Fig. 40 is far below that of Fig. 39, and this explains why the internal loss was less in the former instance, as this loss is a product of the current-strength in amperes and the internal resistance.

130. In looking at the formula (*b*), $C = \frac{s\,e}{s\,r + R}$, it will be noticed that R, if very small in comparison with r, may be omitted and the formula will then read $C = \frac{e}{r}$, which means

that, if the cells are placed in series, the voltage, amperage, and resistance will be simply those of *1 cell* if the *external* resistance is very *small* in comparison with the internal resistance. On the other hand, if the *external* resistance is very *large* compared with the internal, the latter may be omitted, and the formula will then read, $C = \frac{s\,e}{R}$; that is, the current-strength increases with the number of cells.

131. Summary.—Taking formula (c), $C = \dfrac{e}{\frac{r}{p} + R}$, under consideration, we find the conditions somewhat different. If R is so *small* in comparison with r' that it may be omitted, we have $C = \dfrac{e}{\frac{r}{p}}$, or, in other words, when all the cells are placed in parallel, and the external resistance is very small, the E. M. F. is the same as that of 1 cell, while the total resistance is reduced in proportion to the number of cells. If R is very *large*, $C = \frac{e}{R}$; the E. M. F. would then be that of 1 cell, and the resistance would correspond to the external resistance.

Recapitulating our deductions, we have:

If R is very *large*, compared with r',
$C = \frac{s\,e}{R}$, when cells are in *series*.
$C = \frac{e}{R}$, when cells are in *parallel*.

If R is very *small*, compared with r',
$C = \frac{e}{r}$, when cells are in *series*.
$C = \dfrac{e}{\frac{r}{p}}$, when cells are in *parallel*.

We see, therefore, that *for a large external resistance the series arrangement is the more suitable; while for a large current, through a small external resistance, the parallel arrangement will be more serviceable.*

The arrangement in series is therefore always used in percutaneous applications and the arrangement in parallel in light

and cautery-work. The following examples and diagrams will illustrate this more fully.

132. Large External Resistance.—It is supposed that R is *very large* compared with r' There are, say, 50 cells with an E. M. F. of 1.1 volts each, and an internal resistance of .6 ohm; the external resistance is 200 ohms.

Then,

$$n = 50.0;$$
$$e = 1.1;$$
$$r = .6;$$
$$R = 200.0.$$

Placing the cells in *series*,

$$C = \frac{s\,e}{R} = \frac{50 \times 1.1}{200} = \frac{55}{200} = .275 \text{ ampere.}$$

If we retain the internal resistance,

$$C = \frac{50 \times 1.1}{50 \times .6 + 200} = \frac{55}{30 + 200} = \frac{55}{230} = .239 \text{ ampere.}$$

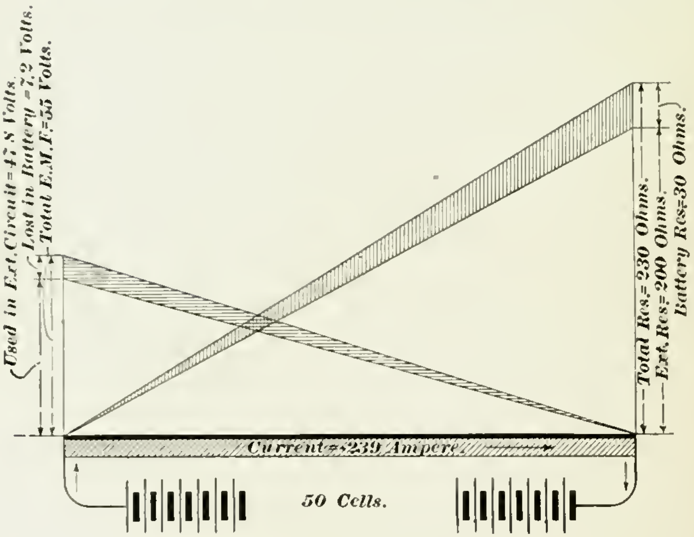

FIG. 42.

Fig. 42 shows that the volts lost in the battery were 7.2, while those utilized in the external circuit were 47.8; total, 55 volts.

Arranging the cells in parallel, as in Fig. 43, we find

$$C = \frac{1.1}{200} = .0055 \text{ ampere.}$$

If we consider the internal resistance,

$$C = \frac{1.1}{\frac{.6}{50} + 200} = \frac{1.1}{.012 + 200} = .00549 \text{ ampere.}$$

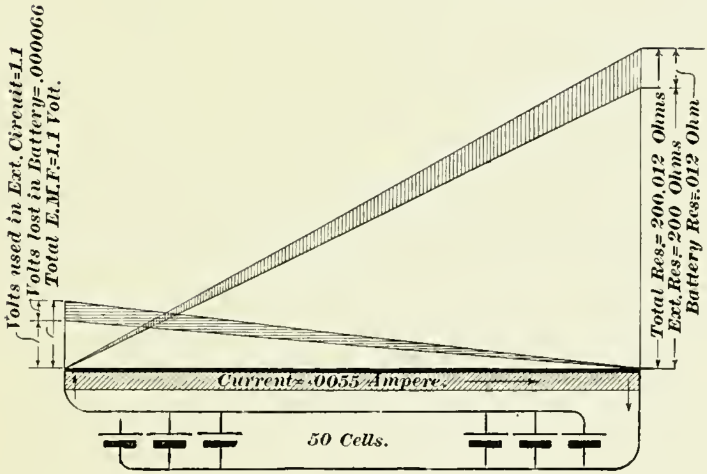

FIG. 43.

Volts lost in battery = .00006588, and volts consumed in exterior circuit = 1.1; total, 1.1 volts.

133. Small External Resistance.—Taking the case where R *is very small* compared with r', with the same number of cells, but with an external resistance of .001 ohm only, we have

$$n = 50.0;$$
$$e = 1.1;$$
$$r = .6;$$
$$R = .001.$$

Placing the cells in *series*,

$$C = \frac{e}{r} = \frac{1.1}{.6} = 1.833 \text{ amperes.}$$

Volts lost in the battery, 54.999; volts utilized in the external circuit, .00183; total, 55.001 volts. (See Fig. 44.)

Again, placing the cells in *parallel*,

$$C = \frac{e}{\frac{r}{p}} = \frac{1.1}{\frac{.6}{50}} = \frac{1.1}{.012} = 91.7 \text{ amperes.}$$

In this instance, the adding of the external resistance affects

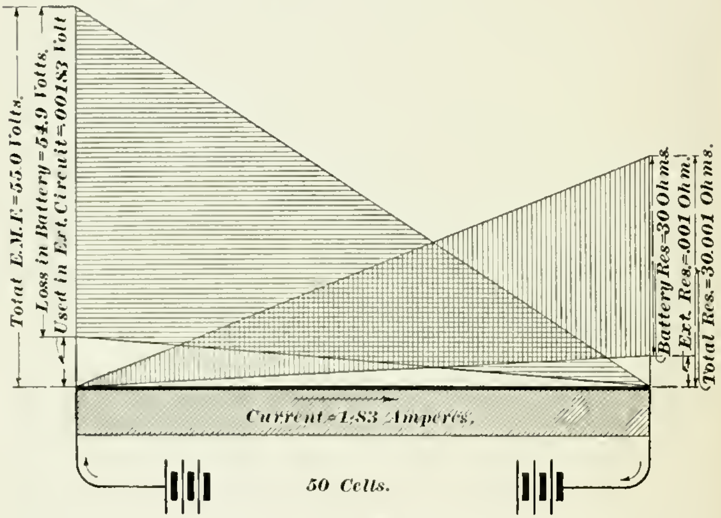

FIG. 44.

the result more than in the former examples. Retaining R, we have,

$$C = \frac{1.1}{\frac{.6}{50} + .001} = \frac{1.1}{.012 + .001} = \frac{1.1}{.013} = 84.6 \text{ amperes.}$$

1.02 volts were lost in the battery and .08 volt in the external circuit, making a total of 1.1 volts.

The diagram in Fig. 45 illustrates the conditions in the circuit.

134. Maximum Current.—The internal resistance of a battery was shown in formula (a), Art. **128**, to be $\frac{s\,r}{p}$, that is, the internal resistance of 1 cell multiplied by the number of

cells in *series*, and divided by the number of cells in *parallel*. This formula is quite useful when it is necessary to decide upon the most advantageous arrangement of cells for sending a maximum current through a fixed external resistance. It can be proved that *a maximum current is sent through a given external resistance, when the resistance of the battery is equal to the external resistance.*

If an arrangement of the cells is found such as to make the current flowing through the circuit a maximum, it follows that the power developed in the external circuit will *also* be a maximum, because the watts furnished are equal to the square of the

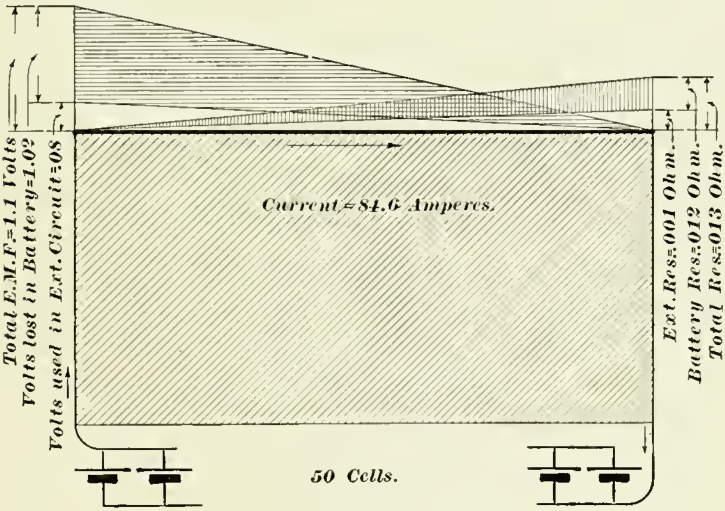

FIG. 45.

current multiplied by the resistance, or $W = C^2 \times R$. Consequently, as the current is at its maximum strength, the power must likewise be so. If, therefore, one-half of the total resistance is situated in the battery, one-half of the total power must also be lost in heating the battery, and the other half be doing useful work in the external circuit.

135. The law as first stated will therefore read as follows: *When the resistance of the battery is equal to that of the external*

circuit, a maximum current will flow through the circuit, and of the total power developed one-half will be lost in heating the battery, while the other half is doing useful work in the external circuit.

EXAMPLE.—If it be required to send a maximum current through an external resistance of 20 ohms by means of 108 cells, each cell having an internal resistance of 15 ohms, how must the cells be arranged?

SOLUTION.—Using the formula (a),

$$C = \frac{s\,e}{\frac{s \times r}{p} + R},$$

it is clear that, in order to make the internal resistance of the battery equal to that of the external circuit, $\frac{s \times r}{p}$, which is the resistance of the battery, must be equal to R, the external resistance. Therefore, $\frac{s \times r}{p} = R$, or $\frac{s \times 15}{p} = 20$. We have also the equation $s \times p = 108$. Inserting the value, $p = \frac{108}{s}$, in the former equation, it will be: $\frac{s^2 \times 15}{108} = 20$. Therefore, $s^2 = \frac{20 \times 108}{15} = 144$, and $s = 12$, and $p = \frac{108}{s} = \frac{108}{12} = 9$. The cells must be arranged 12 in series and 9 in parallel. Ans.

The preceding calculations may be summarized in the two following formulas:

$$s = \sqrt{\frac{n \times R}{r}}. \qquad (d)$$

$$p = \sqrt{\frac{n \times r}{R}}. \qquad (e)$$

136. If we now use the equation, $C = \frac{s\,e}{\frac{s\,r}{p} + R}$, and make the internal resistance $\frac{s\,r}{p} = R$, and also substitute the value for s found in equation (d), we have,

$$C = \frac{\sqrt{\frac{n\,R}{r}} \times e}{R + R} = e\,\frac{\sqrt{\frac{n\,R}{r}}}{2\,R}; \text{ or, } C = \frac{e}{2}\sqrt{\frac{n}{R\,r}}. \qquad (f)$$

This formula gives the maximum current which can be obtained from a given number of cells (n) through a given external resistance (R).

If C is known, and the number of cells is required, the formula may be used in this form :

$$n = \frac{4\,C^2 R\,r}{e^2} \qquad (g)$$

As formulas (f) and (g) are based on the supposition that the internal and external resistances are exactly the same, they are only approximately correct, because it is rarely possible to make them absolutely the same. We will see this more clearly by the two following examples :

Example.—It is required to send a current of .2 ampere through an external resistance of 15 ohms. How many cells are needed, when each cell has an E. M. F. of 1 volt and a resistance of 10 ohms? How many cells in series and parallel are needed?

Solution.—Formula (g) gives

$$n = \frac{4\,C^2\,R\,r}{e^2} = \frac{4 \times .04 \times 15 \times 10}{1} = 24 \text{ cells. Ans.}$$

The number of cells in series is found by formula (d), in which,

$$s = \sqrt{\frac{N\,R}{r}} = \sqrt{\frac{24 \times 15}{10}} = 6. \quad \text{Ans.}$$

The set in parallel,

$$p = \sqrt{\frac{N\,r}{R}} = \sqrt{\frac{24 \times 10}{15}} = 4. \quad \text{Ans.}$$

In this instance, the internal resistance is $\frac{s\,r}{p} = 15$, and therefore equal to the external resistance.

If all the 24 cells were put in series, the conditions would be entirely different. The voltage would be $24 \times 1 = 24$, instead of 6, as at present, but the internal resistance would increase to $24 \times 10 = 240$ ohms, while the current would be only .0941 ampere. In the present arrangement it is .2 ampere, or more than twice as large. The diagrams, Figs. 46 and 47, will illustrate this more clearly.

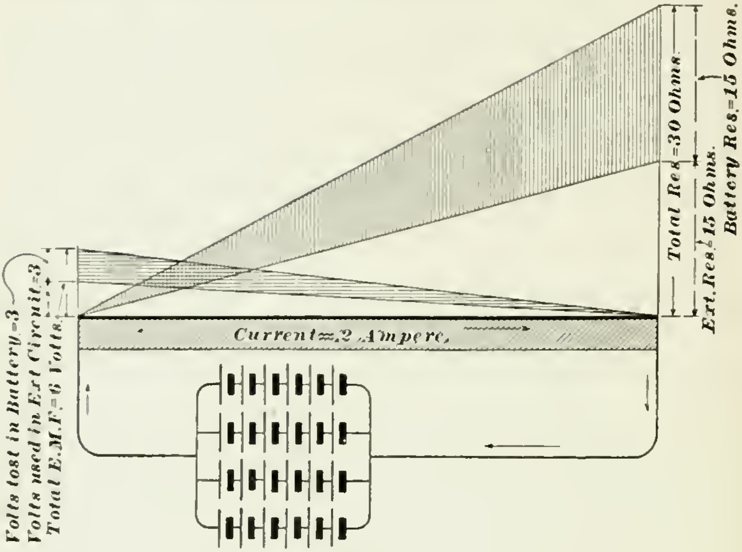

FIG. 46.

By studying these diagrams some very important deductions may be made. We have seen that, in order to have a maximum current from a given number of cells, it is necessary that the

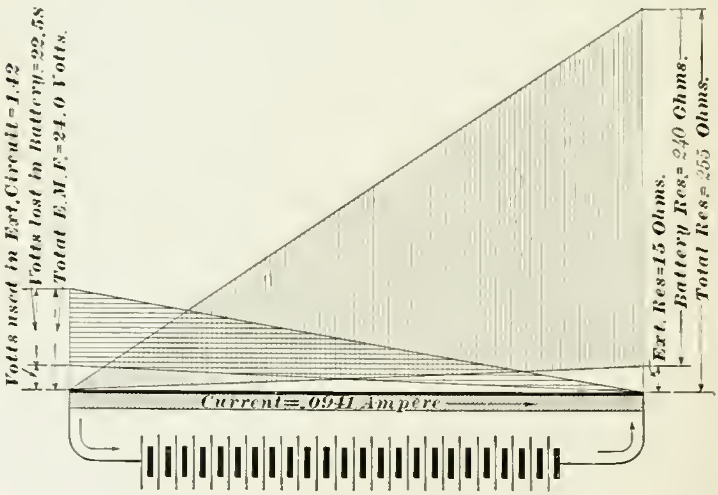

FIG. 47.

internal resistance of a battery be equal to the *external* resistance of the circuit. It follows from this that the total E. M. F. should be equally divided between the battery and the external resistance, or as nearly so as possible. In Fig. 46 we find all of these conditions fulfilled, as 3 volts are consumed in the battery and 3 volts in the external circuit. The triangles representing voltage are alike, as are those representing resistance. The relations between them—that is, between those representing voltage and those representing resistance—determine the strength of the current; the greater the resistance in proportion to the voltage, the smaller the current.

In examining Fig. 47 we find the conditions are not the same as in Fig. 46. In the former diagram there is a great difference in the size of the triangles; the volts consumed in the battery are far in excess of those used in the external circuit, showing that most of the pressure has been expended in the battery itself. The resistance of the battery is also sixteen times as great as that of the external circuit. Though the total E. M. F in the present instance is four times as great as in Fig. 46, the strength of the current is less than one-half.

137. Equal Internal and External Resistance.—We will now take a combination of cells with which it is impossible to make the internal exactly equal to the external resistance, and see how this difficulty may be overcome.

Example.—How many cells will be required to send a current of .75 ampere through an external resistance of 294 ohms? The cells at disposal have an E. M. F. of 1.1 volts each, and an internal resistance of .8 ohm.

Solution.—Using formula (g), we have

$$n = \frac{4\,C^2\,R\,r}{e^2} = \frac{4 \times (.75)^2 \times 294 \times .8}{1.21} = \frac{4 \times .5625 \times 294 \times .8}{1.21}$$

$$= \frac{529.2}{1.21} = 437.4 \text{ cells, or, say, 438 cells. Ans.}$$

Let us see if this number is sufficient. Placing all the cells in series, we have a total E. M. F. of 481.8 volts. The resistance of the battery is then $438 \times .8 = 350.4$ ohms. Therefore, the

volts consumed by the same, $350.4 \times .75 = 262.8$ volts, and the volts used in the external resistance, $294 \times .75 = 220.5$; in all, therefore, 483.3 volts are required. As all the cells in series could furnish 481.8 volts only, there is a deficiency of 1.5 volts. We also see that the resistances are not equal, and that, therefore, the answer is not quite correct.

By adding 3 cells, making the total number of cells 441, the E. M. F. is increased to 485.1. The battery resistance is hereby increased to 352.8 ohms, which, together with the external resistance, makes a total of 646.8 ohms. Volts consumed in the battery will be $352.8 \times .75 = 264.6$, and in the external

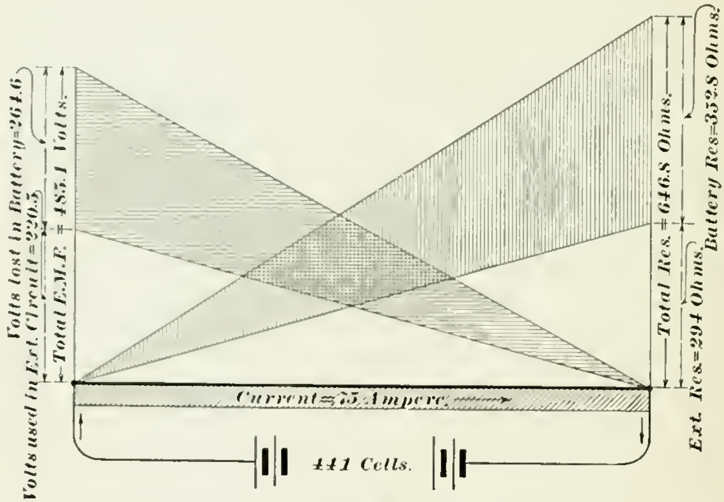

FIG. 48.

resistance, 220.5 volts as before; in all, $264.6 + 220.5 = 485.1$ volts, which is exactly the amount available. Fig. 48 gives the arrangement as finally adopted.

Suppose that in the above problem the volts at disposal were not exactly the number required; say they were 485.8. This amount, while not exactly that required, is sufficiently near for all practical purposes, and would usually be adopted.

An exact solution of these problems is possible only by means of differential calculus, and without it most of the

arrangements of batteries of a more complex nature can be solved only approximately.

EXAMPLE.—It is desirable to know how large a current a battery of cells, each having an E. M. F. of 1.1 volts and a resistance of .6 ohm, will send through an external resistance of 5 ohms, if the cells be formed 4 in series and 3 in parallel.

SOLUTION.—Using formula (*a*) Art. **128**, we have,

$$C = \frac{s\,e}{\frac{s\,r}{p} + R} = \frac{4 \times 1.1}{\frac{4 \times .6}{3} + 5} = \frac{4.4}{5.8} = .76 \text{ ampere. Ans.}$$

EXAMPLE.—If the current in the last example should be increased to 1 ampere and the external resistance to 8 ohms, how many cells in series would be required?

SOLUTION.—By rearranging equation (*b*) for finding *s*,

$$s = \frac{C \times R}{e - C\,r} = \frac{1 \times 8}{1.1 - 1 \times .6} = \frac{8}{.5} = 16 \text{ cells. Ans.}$$

EXAMPLE.—Is it possible, with the conditions as stated in the previous example, to increase the current to 2 amperes by increasing the number of cells?

SOLUTION.—Using the formula for *s*, we have

$$s = \frac{2 \times 8}{1.1 - 2 \times .6} = \frac{16}{-.1} = -160.$$

This is a negative quantity, and it is therefore impossible by adding any number of cells in series to increase the current to 2 amperes. Ans.

138. Let us find the reason for this. Evidently when the cells are in series, the current of the whole series when short-circuited is that of 1 cell—that is the maximum current they will be able to furnish. The maximum current that 1 cell can send is $\frac{1.1}{.6} = 1.83$ amperes. If the number of cells is increased, the resistance will increase in the same proportion; thus, $\frac{1.1 \times s}{.6 \times s}$, and the quotient will therefore be the same—always the amperage of 1 cell—and if there is an additional external resistance, the current will be still less. It will now

be understood why in the last instance it will be impossible to furnish a current of 2 amperes.

Fig. 49 shows that *increasing the number of cells in series will not increase the current when the cells are short-circuited.* The current of 1 cell was found to be 1.83 amperes, and we find the current of 3 cells to be $\frac{3.3}{1.8} = 1.83$ amperes, as with 1 cell, and so with any number of cells. Even should we use the 160 cells given as an answer to the last problem, we find they will give a current of 1.69 amperes only. Going yet further and placing

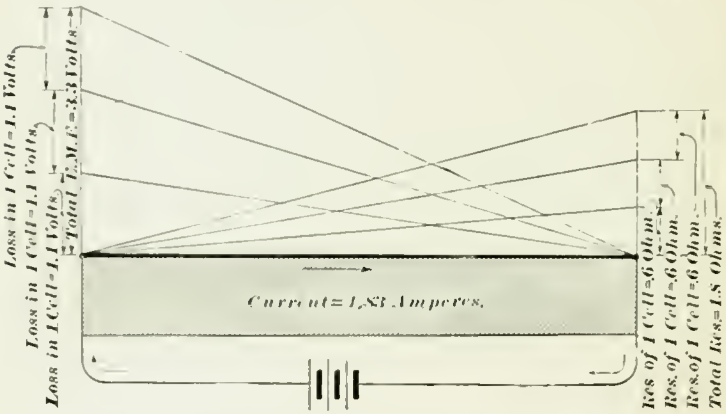

FIG. 49.

1,000 cells in series, with the external resistance of 8 ohms, the current will be 1.80 amperes, and has even then not reached the amperage of 1 cell, namely 1.83 amperes.

139. Placing Cells in Series.—If any difficulty is found in making the total internal resistance equal to the external resistance, it is better to make the internal resistance *larger.* To accomplish this, it will be necessary to put more cells in series and less in parallel, resulting in a higher resistance, but also in a stronger current.

A number of examples will now be given to show the application of the formula for finding the most efficient arrangement for cells.

EXAMPLE.—It is desired to light an incandescent lamp of 50 volts by sending a current of .5 ampere through it. The cells on hand have an E. M. F. of 1.6 and an internal resistance of .1 ohm. If the cells are placed in series, what is the smallest number that should be used?

SOLUTION.—Formula (*b*) will be used, viz., $C = \frac{s\,e}{s\,r - R}$; solving for s, we have, $s = \frac{C\,R}{e - C\,r}$.

Before proceeding further, it will be necessary to find the resistance of the lamp; from Ohm's law, $R = \frac{E}{C}$, we find $R = \frac{50}{.5} = 100$ ohms, and by inserting this in the equation, we have

$$s = \frac{.5 \times 100}{1.6 - .5 \times .1} = 32.3 \text{ cells in series. Ans.}$$

Thirty-two cells would not be quite enough, and 33 would give a current somewhat too large. By interposing a small resistance, the current could be reduced to .50 ampere from .511 ampere, which the battery would otherwise deliver at the pressure of 51.15 volts.

140. This problem can be solved in another manner. We know that each cell suffers a certain loss in voltage, depending on its resistance and the current passing through it; that is, the loss in volts is $C \times r$. Deducting this loss from the E. M. F. of the cell, we will find the E. M. F. available at its terminals. Dividing the required E. M. F by the available E. M. F. of 1 cell, we find the number of cells required. In the present instance the E. M. F. of each cell is 1.6 volts, and the voltage lost in the cell is $C \times r = .5 \times .1 = .05$ volts. Deducting this from 1.6 volts leaves 1.55 available E. M. F. from each cell. The required number of cells is then simply found by dividing the total E. M. F. of 50 volts by 1.55, that is, $\frac{50}{1.55} = 32.3$ cells, as before. Written as a formula, it would read $s \times e - C \times s \times r = V$, V being the available E. M. F. of a battery. As $s \times e = E$, and $C \times s \times r = C \times r'$, then

$$V = E - C\,r'. \qquad (h)$$

EXAMPLE.—In the last example, what is the resistance that must be added in order to reduce the current from 33 cells to .5 ampere?

SOLUTION.—From Ohm's law, we know that $R = \frac{E}{C}$. In this instance, however, R consists of the lamps, battery, and the unknown resistance; the formula must therefore read, if R_l stands for the resistance of the lamp, as follows:

$$R_l + r' + X = \frac{33 \times 1.6}{.5} = 105.6 \text{ ohms.}$$

If we now deduct from this result the known resistances of the lamp and battery, we will in the remainder have the required resistance.

$$X = 105.6 - (100 + 3.3) = 2.3 \text{ ohms. Ans.}$$

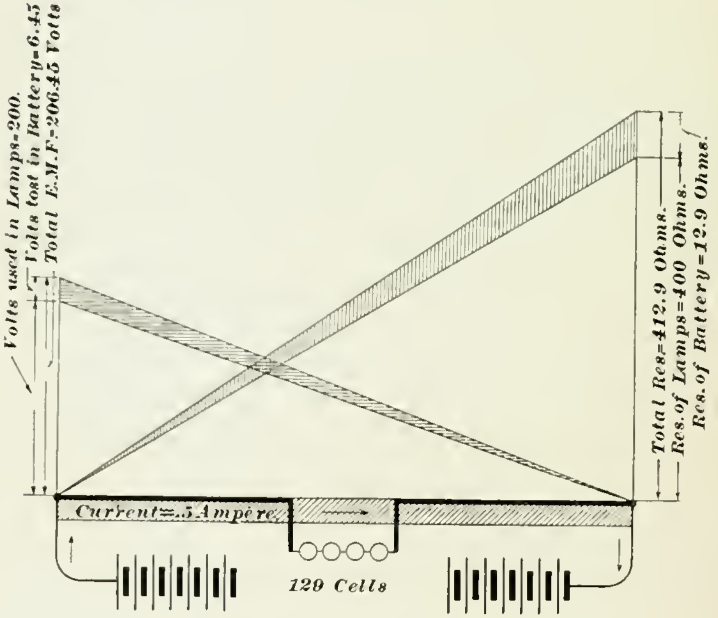

FIG. 50.

EXAMPLE.—Taking the same cells as before—that is, each of 1.6 volts and .1 ohm, but with 4 lamps of 50 volts each and .5 ampere—it is desired to find the most favorable arrangement of lamps and cells to require the least number of the latter.

SOLUTION.—We will first see the effect of placing all the lamps and cells in series. Four lamps in series will need $4 \times 50 = 200$ volts, and V must therefore be equal to this: $V = s e - C s r$; therefore,

$$s = \frac{V}{e - Cr} = \frac{200}{1.6 - .5 \times .1} = 129.03 \text{ cells in series.}$$

Let us now see the effect of placing all the lamps in parallel and cells in series, as before. With all the lamps in parallel, the required E. M. F. would be 50 volts only, but the amperage would be increased to $4 \times .5 = 2$ amperes. Therefore,

$$s = \frac{50}{1.6 - 2 \times .1} = 35.7, \text{ or } 36 \text{ cells. Ans.}$$

This arrangement would therefore require about one-fourth of the number of cells previously found necessary, and with a

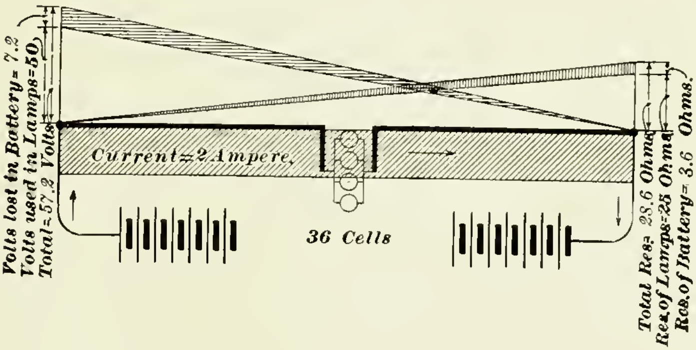

FIG. 51.

small resistance would fill the requirements. Fig. 50 illustrates the effect of placing the lamps in series, and Fig. 51 that of placing them in parallel.

It might probably be more advantageous to place the lamps two in series and two in parallel, and the cells in two parallel series. The lamps would then need a voltage of $2 \times 50 = 100$, and a current of $2 \times .5 = 1$ ampere.

For one set of cells in series, we would have $s = \dfrac{V}{e - r\dfrac{C}{2}}$,

using $\dfrac{C}{2}$ because each set of cells sends one-half only of the total current.

$$s = \frac{100}{1.6 - .1 \times .5} = \frac{100}{1.55} = 64.5 \text{ for one set,}$$

or 129 cells in all, the same as in the first combination.

Let us now try one more combination—that of leaving the lamps as in the last arrangement—and place all the cells in series again. Taking the formula $s = \dfrac{V}{e - Cr}$, we have

$$s = \frac{100}{1.6 - .1 \times 1} = 66 \text{ cells in series.}$$

We see, therefore, that the second arrangement—all the lamps in parallel and the cells in series—requires the least number of cells. In examining Figs. 50 and 51, the conditions are more clearly presented. It is, for instance, noticed that the loss in the battery is very nearly the same in both instances, although the current in one instance is four times as great. On the other hand, the battery resistance in Fig. 50 is about four times as large as in Fig. 51, on account of the greater number of cells necessary for the high E. M. F. It is seen how important it is to lower the internal resistance of the battery, and thus reduce the energy expended in sending the current through the cells. It is for this reason that accumulators are superior by reason of their small internal resistance. To give an opportunity of comparison, we will calculate the number of cells needed to light the same number of lamps used in the last example.

Example.—Four lamps in parallel, each of 50 volts and .5 ampere, are to be lighted by accumulators. How many cells are needed in series when each cell has an E. M. F. of 1.95 volts, and .005 ohm internal resistance?

SOLUTION.— $s = \frac{V}{e - Cr}$; four lamps in parallel = 50 volts and 2 amperes.

$$s = \frac{50}{1.95 - 2 \times .005} = \frac{50}{1.94} = 26 \text{ cells. Ans.}$$ (See Fig. 52.)

141. Electric Power of a Cell.—We have seen, in Art. **18,** that the unit of electric power is the *watt*, and that it

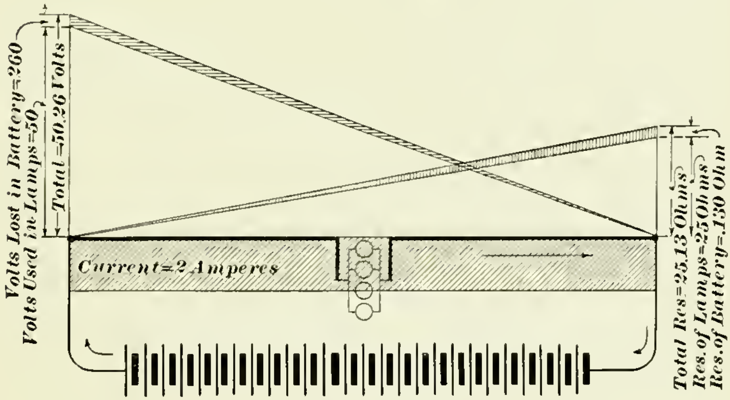

FIG. 52.

is the product of the current in amperes by the E. M. F. in volts. If the power in watts is called W, we have $W = E \times C$, and by substituting in this equation the values of E or C, as found by Ohm's law, we have also $W = \frac{E^2}{R}$, and $W = C^2 \times R$. Again, using e as the E. M. F. and r as the resistance of 1 cell, we find the electric power of 1 cell to be $W = \frac{e^2}{r}$.

As we have stated in Art. **134,** a battery works at its greatest advantage if the internal resistance is equal to the external resistance; the battery is then in reality in a position in which its own resistance, so to say, has been doubled. If we double the resistance, the amperage is halved, the total activity in watts is therefore also halved, and, as half of this power is spent in the battery and the other in the external circuit, it is clear

that the latter will receive one-fourth only of the whole power of the cell.

An example will make this clearer. Suppose we again take the cells used in the last examples, where each cell has an E. M. F. of 1.6 volts and an internal resistance of .1 ohm. Let us take 5 cells, which give a total E. M. F. of $5 \times 1.6 = 8.0$ volts, and a total internal resistance of $5 \times .1 = .5$ ohm. By placing these cells in short circuit, the current would be $C = \frac{E}{r'} = \frac{8.0}{.5} = 16$ amperes. (See Fig. 53.) The total power in watts expended is $W = E \times C = 8 \times 16 = 128$ watts.

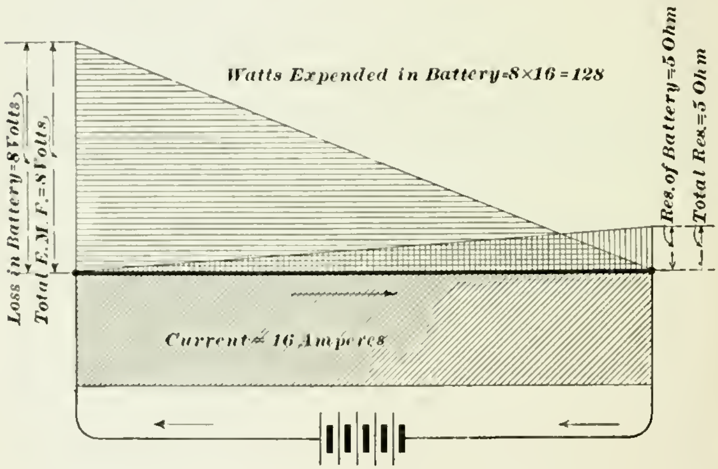

FIG 53.

Therefore, the power in watts, $W = E \times C = 8.0 \times 16 = 128$ watts. Adding an external resistance R exactly equal to r', we have $R + r' = .5 + .5 = 1.0$ ohm; this is then the total resistance of the circuit. The current will now be,

$$C = \frac{E}{R + r'} = \frac{8.0}{1.0} = 8 \text{ amperes.}$$ (See Fig. 54.)

The total activity in watts, $W = E \times C = 8 \times 8 = 64$ watts, that is, one-half of that of the battery on short circuit. The resistance of the internal and external circuits being the same, the same amount of E. M. F. will be spent in each, i. e.,

one-half of the total. As 8 volts is the E. M. F. of the battery, 4 volts will be spent in the battery and 4 volts in the external

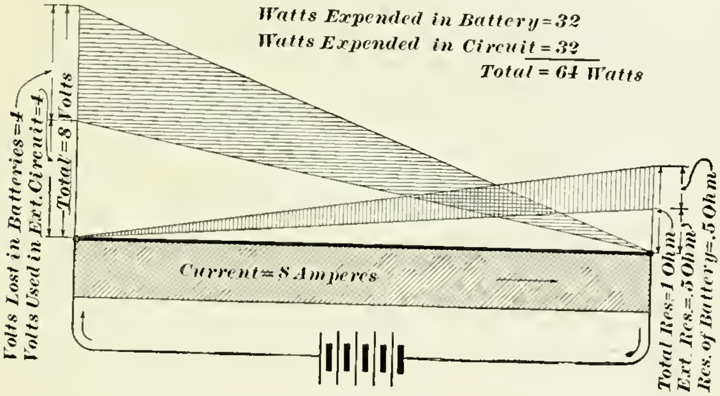

FIG. 54.

circuit. The power spent in either will then be $4 \times 8 = 32$ *watts*, which is just one-fourth of the battery power, 128 watts.

142. We see from this that, if it is desirable to spend electric power amounting to that of *1 cell* in an internal circuit, it is necessary to have the battery consist of at least *4* cells. Therefore, if W is the power in watts which is to be delivered to an external circuit, the needed number of cells will be $n = \frac{4W}{\frac{e^2}{r}}$, $\frac{e^2}{r}$ being, as shown above, the power of 1 cell. The formula may be more conveniently used in this form, $n = \frac{4Wr}{e^2}$.

EXAMPLE.—It is required to develop a power of 192 watts in an external circuit. The cells on hand have an E. M. F. of 1.6 volts and internal resistance of .1 ohm. What is the least number of cells required?

SOLUTION.—The formula $N = \frac{4Wr}{e^2}$ will give us the number required.

$$n = \frac{4 \times 192 \times .1}{1.6 \times 1.6} = \frac{4 \times 192 \times .1}{2.56} = 30 \text{ cells. Ans.}$$

Let us see if this answer is correct. From former statements we know that the external resistance must equal the battery resistance; therefore, the same number of watts must be spent both in the battery and in the external circuit, because the current is the same. By placing all the cells in series and on short circuit, they develop an E. M. F. of $30 \times 1.6 = 48$ volts, and show an internal resistance of $30 \times .1 = 3$ ohms. The current will then be $C = \frac{E}{r'} = \frac{48}{3} = 16$ amperes, and the power developed in watts $16 \times 48 = 768$.

The introduction of the exterior resistance changes this, and $\frac{48}{2} = 24$ volts must now be spent in the external circuit, leaving 24 volts only for the battery. The total current will then be $\frac{24}{3} = 8$ amperes only, and, as this same current also passes through the external circuit, the number of watts spent in the latter will be $V \times C = 24 \times 8 = 192$. The watts W spent in both parts of the circuit is $E \times C = 24 \times 8 = 192$. The sum of these (384 watts) is, as was proved above, only one-half of the battery power, which was found to be 768 watts.

In this example, the cells were put in series, but not necessarily so. The 30 cells might have been placed in any other combination, and the power in watts developed would have been exactly the same. The proper arrangement is determined by the pressure in volts desired in the external circuit, and the cells must be arranged as previously explained, to furnish this pressure.

143. Capacity of a Cell.—There is yet another point which requires some attention. In the last example, we found that the cells on short circuit were able to furnish a current of 16 amperes; but of this amperage one-half only was used, that is, 8 amperes. It is possible that this is beyond the capacity of the cell, and that polarization would set in—in fact, that 6 amperes would be the maximum current which the cell would be able to furnish. In this case, the formula quoted above must be modified. If we call this reduced current-strength c,

then $c \times e$ is the maximum power the cell is able to deliver, and $c \times e - c^2 \times r$ is the maximum power it is possible for it to deliver in the external circuit.

The formula, $n = \frac{4\,W r}{e^2}$, must then be changed to this form:

$$n = \frac{W}{c \times e - c^2 \times r}$$

Example.—Taking the conditions of the last example, in which the external power required was 192 watts, and the cells with an E. M. F. of 1.6 volts and an internal resistance of .1 ohm, we found that the cells delivered a current of 8 amperes to the circuit. If the current is limited to 6 amperes, how many cells will be required?

Solution.—The new formula gives

$$n = \frac{W}{c \times e - c^2 \times r} = \frac{192}{6 \times 1.6 - 36 \times .1} = \frac{192}{6.0} = 32 \text{ cells. Ans.}$$

This change in the number of cells of course requires a rearrangement of the same, which is done according to the rules already given.

CLASSIFICATION OF ELECTROMOTIVE FORCES.

144. Variations in E. M. F.—Electromotive forces, as produced by various appliances, are alike in their tendency to start an electric current, but they are often very dissimilar in other respects. Some devices, as, for instance, a primary battery or a direct-current dynamo, produce electromotive forces that are practically constant in strength; again, in others, such as frictional machines, the E. M. F. is more or less variable, while finally, in alternators and induction-coils, we find the E. M. F. not only varying in strength, but also in direction, periodically changing from a positive to a negative E. M. F., or vice versa.

These variations may be very clearly shown graphically by means of a curve on cross-section paper, the method usually adopted being to let the *ordinates*, or vertical distances, represent the E. M. F., and the *abscissas*, or horizontal distances, represent intervals of time.

GRAPHICAL REPRESENTATION OF PRESSURE.

145. To make the subject clearer, we will again use as an analogy the flow of water from a tank through a tube at a constant pressure. Let the pressure be 4.5 pounds per square inch, and the water in the tank be kept at a constant level. The conditions may then be represented by means of the diagram in Fig. 55. Here the vertical line *A C* at the left measures off the pressure in pounds, and the horizontal line *A B* indicates the time in seconds. The line *D E* is then laid off at a distance from *A B* corresponding to 4.5 pounds.

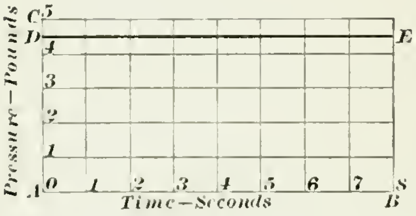

FIG. 55.

The fact that the line *D E* is entirely parallel to *A B* proves that throughout the time of 8 seconds the pressure remained constant.

146. Next let us represent the action of the pump shown in Fig. 56. It is supposed that the piston *C*, during a time of 4 seconds, forces the water out though the valve V_1 into the pipe *P'*, and that at the end of the latter the water is delivered at a pressure of 8 pounds per square inch. While the piston returns to its original position, which also takes place during the time of 4 seconds, water is flowing into the cylinder from the pipe *P* through the valve *V*.

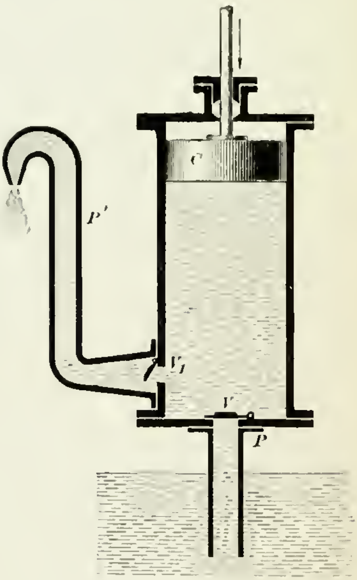

FIG. 56.

The action of the pump, so far as the pipe *P'* is concerned, is intermittent, and if it is required to show the action by means of

a diagram, then Fig. 57 will represent the conditions that exist during the time of 8 seconds. The line DE shows that the pressure in the pipe P' during the time of 4 seconds remained at a constant pressure of 8 pounds; at this point the pressure immediately fell to zero, and remained there during the next 4 seconds, while the piston was returning to its first position.

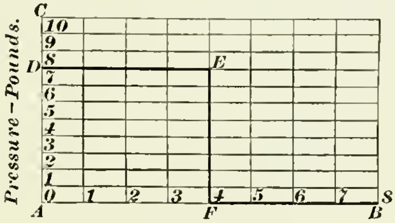

Fig. 57.

147. Let us now represent the action of the pump shown in Fig. 58. Here the water does not leave the pump, but is simply changed from one side of the piston to the other by passing through the pipe P. The latter is provided with an indicator M, which not only measures the pressure, but also indicates the direction. We will call the direction indicated by the arrow v a positive, and the reverse a negative, direction, and will suppose that the pressure remains 8 pounds while the

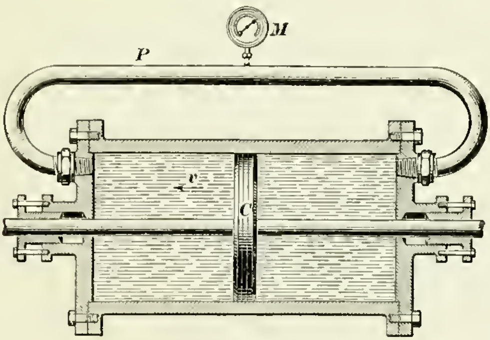

Fig. 58.

piston travels, during the time of 4 seconds, from one end of the cylinder to the other, at which points the pressure falls to zero. Fig. 59, then, illustrates the action of the pump. AB represents the zero-line, and the values marked off above this line are *positive;* below it they are *negative.* When the piston moves from right to left it moves in a positive direction, and

the pressure exerted by it is therefore marked off above the zero-line, by means of the line DE, the point E being the point where the piston stops and where the pressure suddenly falls to zero, as shown by the line EF. The piston is supposed to immediately begin its return-stroke, and the zero pressure is therefore at once changed into a negative pressure of 8 pounds, as indicated by the line FG. This pressure remains constant during the whole length of the stroke, as seen from the line GH. At the point H the pressure is again reversed to a positive one of 8 pounds at D', and the motion is repeated.

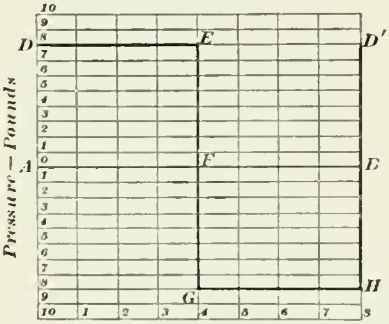

FIG. 59.

The tracings shown in Figs. 55, 57, and 59 will now be used directly for illustrating the main differences between the various forms in which an electromotive force may manifest itself.

DIRECT ELECTROMOTIVE FORCE, OR CURRENT.

148. Direct E. M. F., or Current.—When an E. M. F. tends to act in one direction only it is called a *direct* E. M. F., as distinguished from an *alternating* E. M. F. A direct E. M. F. need not necessarily be constant, in fact it may vary between very wide limits ; but as long as it does not change in direction it will remain a direct E. M. F., and the resulting current a direct current.

149. Continuous E. M. F., or Current.—When a direct E. M. F. has an absolutely constant value during succeeding intervals of time, causing a perfectly steady current to flow in a closed circuit of constant resistance, it is called a *continuous* E. M. F., and the resulting current a continuous current. The

diagram in Fig. 55 will represent an E. M. F. of this class, if the pressure in pounds be replaced by a pressure in volts. A voltaic battery in good condition and a direct-current dynamo will both produce a continuous E. M. F., though in a dynamo the latter will not be quite so uniform, but of a more wavy character, as indicated by the diagram in Fig. 60.

150. Pulsating E. M. F., or Current.—When these waves reach a magnitude as shown by the curve in Fig. 61, it is said to be a *pulsating* E. M. F. Even here, though the difference between the maximum and the minimum pressure is

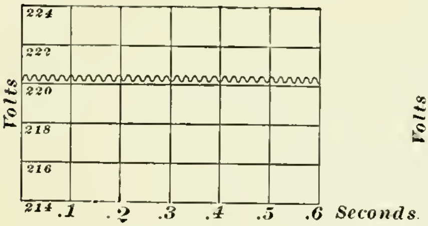

Fig. 60.

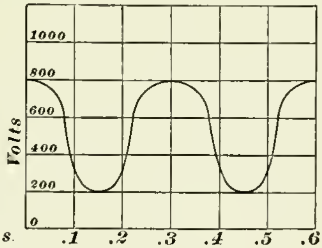

Fig. 61.

about 600 volts, the E. M. F. is still a direct one, as it always remains above the zero-line and therefore does not change direction. A dynamo with few coils in its armature would produce an E. M. F. of a somewhat similar nature; so would a voltaic battery if its current were passed through a rheostat of carbon powder, the resistance of which would change by rapidly varying the pressure on the carbon.

151. Intermittent E. M. F., or Current.—If the E. M. F. periodically falls down to zero and remains there for a short time, as indicated in Fig. 57, then the E. M. F. is said to be *intermittent.*

ALTERNATING E. M. F., OR CURRENT.

152. Alternating E. M. F.—An *alternating* E. M. F. is one that alternately changes in direction. In the form most frequently found it may be said to be an E. M. F. that

constantly changes in magnitude and periodically in direction. Fig. 59 shows a form of alternating E. M. F. which suddenly changes in direction, such as would be the effect if the E. M. F. that a voltaic battery impressed on a conductor were suddenly reversed by means of a commutator. The alternating E. M. F. most frequently found changes its direction more gradually, as seen from the curve in Fig. 62. Here the E. M. F. begins from zero at *A*, rises gradually, while acting in a positive direction, until it reaches *B*, where it has a maximum value of 500 volts; from this point the pressure begins to fall, still remaining positive, until at *C* it again reaches the zero mark. In passing below this point the direction of the E. M. F. changes from positive to negative, and the maximum pressure is attained at *D*, whence it again begins to fall until point *E* is reached, when the E. M. F once more is of zero value. Proceeding from *E* towards *F*, the E. M. F. is positive again, and from there follows a repetition of the curve as begun at *A*.

153. If the curves representing the E. M. F. on either side of the zero-line are exactly of the same shape, but acting in opposite directions, the alternating E. M. F. is said to be *symmetrical*. Figs. 62 and 63 represent curves of symmetrical, and

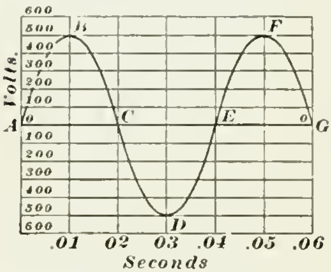

FIG. 62.

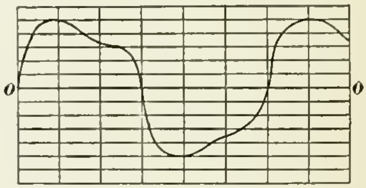

FIG. 63.

Fig. 64 a curve of *dissymmetrical* form, such as may be produced in the secondary coil of an induction-coil.

154. Sine Curves.—The curve shown in Fig. 62 is also called a *sine curve*, or *sinusoid*, and the E. M. F. which it represents is said to be *sinusoidal*.

The nature of a sine curve may be explained by means of Fig. 65, (*a*), (*b*), and (*c*). Let us suppose that a point *a* of (*a*) revolves around the point *o* with a constant velocity, so that the distances *a b*, *b c*, etc. are each covered during the time of 1 second. If the point *a* had been traveling in a direction at right angles to the line $a\,a_1$, for instance, along the line *a h*, the distance traveled along this line would at any time be directly proportional to the time during which the point *a* had been in motion. That is to say, during a time of 6 seconds *a* would be at a distance $6 \times a\,b$ away from the line $a\,a_1$. But when the point *a* performs a circular motion, as in (*a*), the conditions are entirely different.

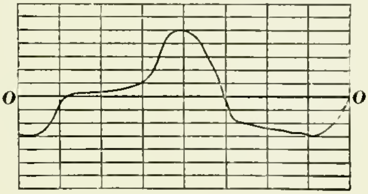

FIG. 64.

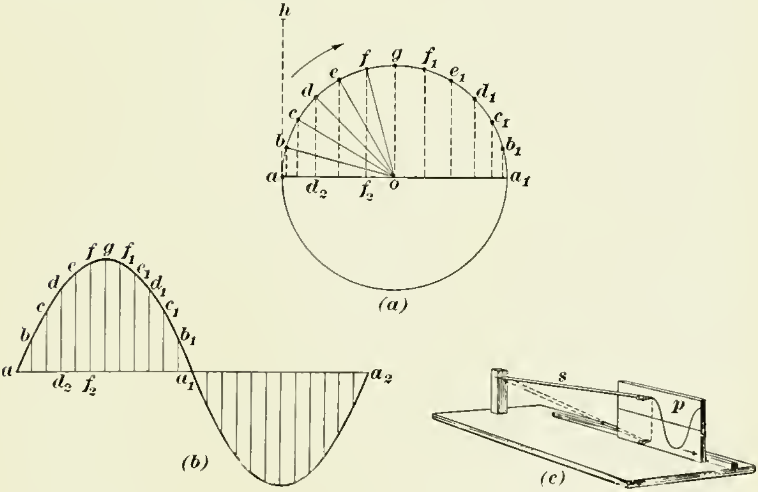

FIG. 65.

The distance between *a* and the line $a\,a_1$ is then no longer directly proportional to the time, but to the sine of the angle through which it has moved relatively to the line $a\,a_1$. For instance, when the point *a* has moved into the position *d*, and,

therefore, through the angle $a\,o\,d$, its distance from $a\,a_1$ is proportional to the *sine* of this angle, or the line $d\,d_2$. Similarly, when a has moved to the point f, its distance from $a\,a_1$ is proportional to the sine $f\,f_2$, and so forth. If, now, the line $a\,a_1\,a_2$ in Fig. 65 (b) is divided into a number of equal parts corresponding to the number of divisions of the circle in Fig. 65 (a), and vertical lines are erected from these points, the signs of the various angles may be laid off on these lines. Thus, $d\,d_2$ corresponds to the sine of angle $a\,o\,d$, and $f\,f_2$ to the sine of $a\,o\,f$, etc. As soon as the point a passes the position a_1, the values of the sines will be negative, and are laid off below the line $a\,a_1\,a_2$, in the manner already described.

When the various points a, b, c, d, etc., thus determined, are connected by means of a curved line, this line will constitute a sine curve. A sine curve is not necessarily limited to the form given in Fig. 65 (b), as it is evident that the relation between the length of the divisions on the line $a\,a_1\,a_2$ and the sines will materially change the appearance of the curve. Thus, by bringing the said divisions more closely together, the curve will assume a more peaked form, while, on the other hand, if the divisions are put farther apart, the waves will appear more shallow.

155. A sine curve may be automatically drawn by means of a vibrating spring. If a long flat spring s, in Fig. 65 (c), is fastened at one end and the other provided with a pencil, the latter will, while the spring vibrates, draw an approximate sine curve on a sheet of paper p moved under the pencil in a direction parallel with the center line of the spring.

156. Cyclic Alternating Currents.—If the curve which represents the E. M. F. of an alternating current is symmetrical on both sides of the zero-line, as the curve in Fig. 62; and if, further, the continuation of the curve is simply a repetition of the first part $A\,B\,C\,D\,E$, then the E. M. F. (or its resulting current) is called a *cyclic*, *periodic*, or *harmonic* alternating E. M. F. or current.

157. Alternations, Cycles, and Periods.—In speaking of a cyclic alternating current, each complete reversal of the

E. M. F., or current, is called an *alternation;* in Fig. 62, for instance, three alternations are represented, as ABC, CDE, EFG, etc.; each alternation lasts, therefore, $\frac{2}{100}$ of a second, and there are 50 alternations per second. Two successive alternations, that is, one positive and one negative wave, constitute a *cycle.* ABC and CDE together constitute one cycle, and the time required for its completion is called a *period;* in the present instance it is .04 second, and the E. M. F. represented by this curve would be said to have a period of .04 second.

158. Frequency.—The number of complete cycles which occur in 1 second is called the *frequency*, and this is indicated by the sign $\sim$. In the example cited above, the number of cycles which occur in 1 second is $\frac{1}{.04} = 25$, so this E. M. F. would be said to have a frequency of 25 $\sim$, or 25 *cycles per second. Frequency* is the reciprocal of *period.*

159. Alternating Current.—The current-strength produced by this varying E. M. F. will not necessarily be proportional to the height of the E. M. F.; it will also depend on the rate at which the E. M. F. increases or decreases in value or changes from positive to negative. If the E. M. F. is continuous, or if the changes are so slow as to more or less avoid the introduction of self-induction, the value of the current-strength will keep step with that of the E. M. F. But when the rate at which these changes take place exceeds a certain frequency, the current will no longer be able to keep step with the E. M. F., but will lag behind and will reach various points in its own cycle a certain length of time *after* the impressed E. M. F. has reached similar points in its cycle. Fig. 66 shows the

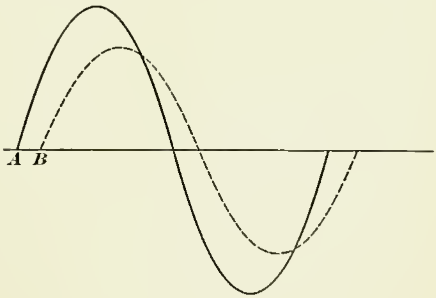

Fig. 66.

effect very clearly. Here *A* is the curve of the E. M. F., which would also be the curve of the resultant current, if the circuit were devoid of self-induction. The curve *B* shows the real strength of the current and the position of its maximum values as related to those of the E. M. F. We see here that the crests of the waves in curve *B* not only lag behind those of *A*, but also fail to reach the same height as those of the latter curve.

MAGNETISM

— AND —

ELECTROMAGNETISM.

Magnetism and Electromagnetism.

NATURE OF MAGNETISM.

1. Electromagnetic Phenomena.—When the subject of electricity in motion was considered, it was seen that the conductor had a certain effect on the flow of the current, it being able to retard it more or less; but in doing so the conductor in return suffered a change, the change being shown by an increase in temperature. In both cases the effects were caused by the passage of an electric current through the conductors and took place in the conductor itself. But in addition to these there are other and very important effects produced by the current, which are not limited to the conductor itself, but take place in the surrounding medium. These phenomena are called *electromagnetic*, and will now be considered more fully.

The relations between electromagnetism and magnetism proper are so intimate that it is difficult to describe one of them without constantly being obliged to refer to the other; they will therefore be treated in the following pages in conjunction with each other.

2. Magnetism as a Science.—It is just as well to say, at the outset, that we do not know any more about the nature of magnetism than we do about that of gravitation and electricity, and that is next to nothing. It is more than likely that magnetism is electricity in rotation. In every case the forces of both are exerted at right angles to each other. All we do know is that certain metals under certain conditions can be made to exert an attractive or repulsive influence on each

other, and all that science has so far accomplished is to formulate the laws under which these forces act and react, and according to these laws certain bodies, as iron, steel, nickel, and cobalt, called *magnetic substances*, may be magnetized and demagnetized, either by means of permanent or electromagnets.

3. Reaction Between Magnets.—In bringing two ordinary magnetic needles in proximity to each other we find they perform certain peculiar, but well-known motions. For instance, on attempting to bring their similarly marked poles opposite to each other, they will refuse such proximity, and a repulsion will take place, resulting in a partial revolution of either needle into new positions, in which the axis of both needles lie in one line, but with differently marked poles adjoining, as shown in Fig. 1.

FIG. 1.

We come then to the conclusion that *the similarly marked poles of magnetic needles repel each other, and differently marked poles attract each other.*

In this country the marked end of a needle or bar magnet is called a *north pole*, the other end a *south pole*, and for the present these terms will be used without explaining their meaning.

4. Experiments With Magnetic Needle.—The knowledge thus acquired we will use for some further investigation of

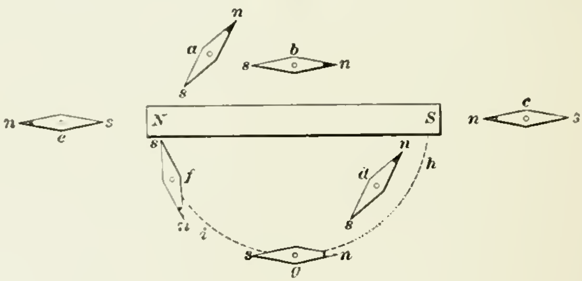

FIG. 2.

the immediate surroundings of a bar magnet, such as is shown in Fig. 2. On bringing a magnetic needle near its sides or ends,

we notice that the position of the needle will vary considerably while it is moving along the sides of the bar.

In position *a* we find the south pole of the needle pointing towards the north pole of the bar, but making an angle of about 75° with the axis of the latter. Moving to position *b*, the needle places itself entirely parallel with the bar, and, on arriving opposite the end of the latter, at *c*, it has placed itself exactly in line with the longitudinal axis of the bar. In the latter position opposite poles are facing each other. Continuing this method of investigation, we arrive at the other side of the magnet and find there similar conditions; at *d* we have its north pole pointing towards the south pole of the bar, making an angle corresponding to that at *a*, and, continuing the circuit, we arrive at last at *e*, where the needle again places itself in line with the axis of the bar, but in this instance with its south pole opposite the north pole of the magnet. If the bar is round, we might, after placing the latter in a vertical position, move the needle in circular horizontal paths around it, and would find some invisible force constantly tending to deflect the needle into positions in which it always is pointing towards the axis of the bar.

5. We will now go a step further and follow a path from one end of the bar to the other, as indicated by the needle itself. Beginning at *f* and following the direction in which the north pole *n* is pointing, we arrive at point *g*, where the needle again is parallel with the bar, and, continuing, we find the termination of the path at *h*.

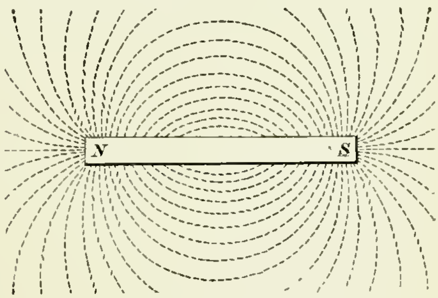

FIG. 3.

By placing the bar magnet on a sheet of paper and indicating, by means of a pencil, the path over which the needle has traveled, we will have drawn a line somewhat similar to the dotted line *h i* in Fig. 2.

In starting from other points, along the sides and ends of the bar magnet, numerous paths may be marked out, so that after awhile we would have a picture somewhat similar to Fig. 3.

A simple way to show the direction of these lines is to dust fine iron filings on a sheet of paper and place this over the magnet, with a plate of glass intervening, when, by gently tapping the glass, the iron filings will arrange themselves in lines corresponding to those of Fig. 4.

6. Lines of Magnetic Force.—*Faraday* made very extensive investigations of magnetism by means of such iron

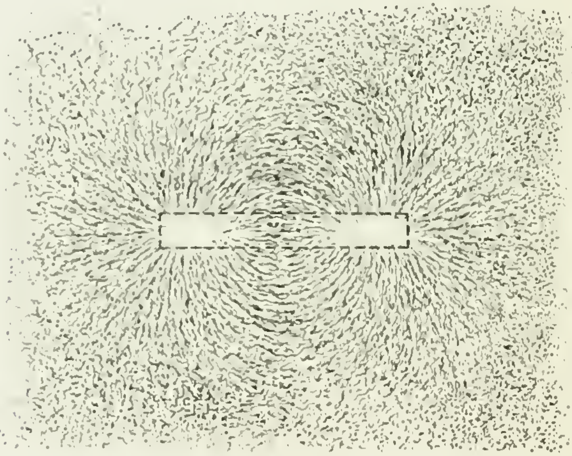

FIG. 4

filings, and the lines which they traced were by him called *lines of magnetic force.* These lines show the direction in which the magnetic force is acting, and also indicate the strength of the force, as they are more numerous and closer together where the intensity of the magnetism is at its maximum. The whole collection of lines of force around the magnet is called the *magnetic field.* The lines of force in a magnetic field, when not disturbed, have only one form of energy, viz., attraction and repulsion. In order to make these lines produce an E. M. F., they must be intersected by some conducting material, and to

obtain an electric current the conducting material must form a circuit.

7. Magnetic Field.—Of course these lines have no actual existence. It is well to remember this, as diagrams similar to Fig. 3 are often understood to mean that the magnetism acts along these lines only, and nowhere else; that is to say, that between these lines the magnetic field is neutral. Evidently this is a misconception; there are no variations in the field as sudden as this, but, on the contrary, a gradual decrease towards the exterior parts of the field.

8. When a magnetic field exists between two magnetic bodies, we have to imagine a certain stress in said field, a tendency to draw the bodies together along the lines of force. We have further to suppose that this attraction is not carried on by means of the surrounding air, but by the aid of the all-pervading *ether*, which also surrounds each individual molecule of the two bodies.

9. Magnetic Flux.—Though we do not know for certain that the electric current actually flows through a conductor, we use this convention as a convenience and determine its direction of flow by investigating its influence on a magnetic needle, as will be shown further on.

In the same manner we speak of the magnetic lines of force as flowing from pole to pole, thus indicating the direction of the *magnetic current*, or *flux*, and also here determine the direction by means of a freely suspended magnetic needle. Thus, in Fig. 2, the needle while moving from position f to h, was traveling with the lines of force.

When a freely-suspended magnetic needle is standing or moving in a magnetic field its north pole will always indicate the direction in which the lines of force at that place are flowing; in fact, we may imagine these lines to *enter the needle at its south pole and leave it at its north pole.* Applying this rule to Fig. 1, the lines of force would come from the extreme left, enter the first needle at its south pole, leave it again at its north pole, to enter the south pole of the other magnet, and so

forth. This rule forms the foundation for all the following experiments, and must be kept clearly in mind.

10. Interactions Between Lines of Force.—We have seen that when unlike poles of two magnets are opposite each other, an attraction takes place. Now, the condition of the magnetic field between these poles is somewhat similar to that which would prevail if the lines of force were replaced by a series of rubber strings under tension, which, to make the similarity complete, should also have a tendency of mutually repelling each other in a lateral direction.

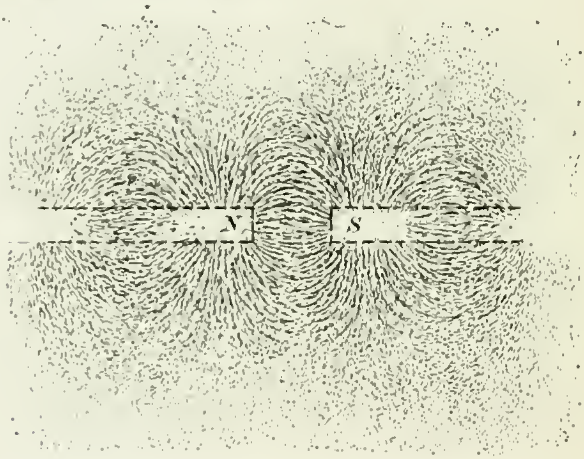

FIG. 5.

Lines of magnetic force running in the same direction have this tendency of repelling each other, while between lines running in opposite directions an attraction takes place. We shall see further on that these interactions also take place between two conductors through which electric currents are flowing.

Figs. 5 and 6 illustrate the interactions between lines of force in two magnets. If, as in Fig. 5, the adjoining poles are of opposite polarity, the lines of force near each of the poles will, before the latter are brought close together, be traveling in opposite directions; but if the bars are so close that an interaction takes place, the lines of force will attract each other

and unite. The contracting tendency of the lines will then begin and the two poles will attract each other.

In Fig. 6 the conditions are reversed, as here two similar poles are facing each other, from both of which lines of force are emanating in the same direction. A repulsion will therefore take place and the lines of force will turn away at right angles to the axes of the two magnets. This repulson of the

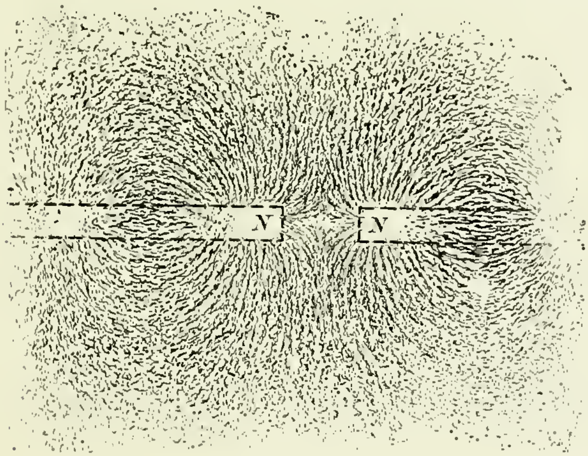

FIG. 6.

lines of force will interact on the molecules of the bars and will also cause a repulsion of the latter.

11. Magnetic Circuit.—We have now seen how in a magnet there is a certain flow of magnetism issuing from its north pole, whence it proceeds in curved paths through the surrounding space along the sides of the bar to its south pole, where it again enters and then traverses the whole length of the magnet. As there is neither end nor beginning to this flow, it constitutes a closed path or circuit, and is therefore called a *magnetic circuit.*

It has also been shown how a freely-suspended magnet, when in a locality where lines of force are passing, will place itself so that its longitudinal axis coincides with the lines of force and so that it points with its north pole in the direction

in which the lines of force are traveling. Finally we found that unlike poles attract and like poles repel each other.

12. Terrestrial Magnetism.—There yet remains one subject with which we have to deal before we proceed any further, and that is the magnetism of the earth. It is a familiar fact that the earth itself constitutes an immense magnet, with a north and south pole, and lines of force traveling through its interior as well as along its surface and through space. The presence of these lines of force has been of great benefit to

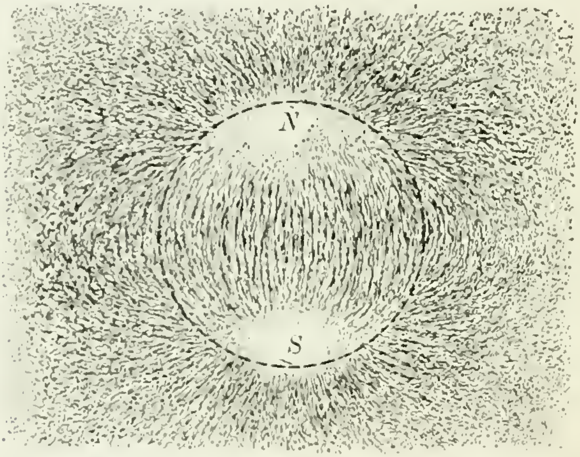

Fig. 7.

travel both on land and sea, in making the use of a compass possible.

In Fig. 7 we find a representation of the form which the lines of force will assume in traveling from pole to pole, and also the directions in which they will move. When applying the information so far derived concerning the position a freely-suspended magnetic needle will occupy while situated in a magnetic field, we come to a conclusion which is not a matter of general knowledge. The magnetic needle of the mariners' compass or any other compass will, as we all know, point towards the terrestrial north pole, or very nearly so, depending on the longitude of the place where it is situated. The lines of force will

therefore enter the needle from the south, pass through it and proceed towards the north. But it has previously been said that the lines of force *leave* the north pole of the magnet; evidently, then, the lines of force coming from the south pole towards the needle must come from a north pole, and we therefore come to the conclusion that the *terrestrial south pole* must be a *magnetic north pole* and vice versa. The magnetic south pole does not coincide with the earth's north pole, but is about 1,000 miles to one side of the latter.

MAGNETIZATION.

13. Two questions will now suggest themselves, to which we will have to find an answer, viz., (1) *Why does a body of iron or steel under certain conditions change from a neutral to a magnetic condition?* (2) *If a piece of steel is magnetized in one of different ways, has it had imparted to it a certain magnetic power not previously existing in it, or, if not, where does this power come from?*

14. Difference Between Electricity and Magnetism. Before attempting to answer these questions let us first consider an important difference between electricity and magnetism. If, for instance, a conductor is charged with electricity and is brought in contact with another conductor, it will give up part of its charge, as will be shown in *Electrostatics*. On discharging and charging the second conductor again and again, the first conductor will finally have given up all of its charge, and both will be neutral.

If this experiment is repeated with a magnet and one or more pieces of steel, the result will be entirely different. We can, for instance, magnetize and demagnetize one piece of steel any number of times, or we can magnetize any number of steel pieces with the same magnet; the result will be the same, that is, the magnet will not give up any of its magnetism or grow weaker. How, then, shall we explain this apparent inexhaustible supply of magnetism?

15. Molecules.—To give an explanation of this phenomenon we have to go to the physical foundation of all matter—to the molecule itself. The exact form of the molecule is not

known, but every indication tends to show that it is more or less globular in form, perhaps slightly elongated. It appears that in a magnetic metal every molecule is in itself a magnet, very much constituted as the globe on which we live. But though we speak of molecules as being magnetic, we must understand this to mean that in reality it is the ether, enveloping each molecule, which exerts the magnetic attraction or repulsion, and not the molecule itself. It was already shown that this was the case with magnets in general, and it also holds good as regards the earth itself. We must therefore imagine each molecule to have its own north and south pole and its neutral equator.

Having this clear in mind, let us now see what are the positions of the molecules in a neutral piece of iron. We have seen that these molecules already are magnetic, and it is therefore of interest to see why it is that they do not show any external magnetism, and how they may be made to exhibit such magnetic effects. When not disturbed by external influences, the magnetic properties of the molecules of a neutral piece of iron are satisfied by the short circuits established between the molecules of the iron.

16. Interaction Between Freely-Suspended Magnetic Needles.—On holding a magnet near an ordinary magnetic needle, the latter will respond to every motion of the former and occupy any position desired. With *two* magnetic needles in close proximity to each other, as shown in Fig. 1, this is no longer the case; they will refuse to move out of line with each other until compelled to do so by a superior force. This interaction is clearly shown by means of Fig. 8, where the needles in position (a) are placed exactly as those shown in Fig. 1, and therefore mutually react on each other so as to keep their axes in line. In this and the following

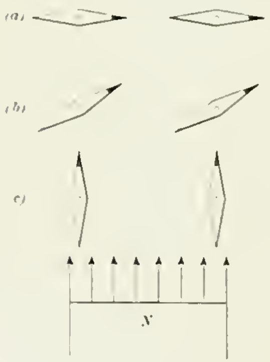

FIG. 8.

figures, the north pole of a needle will be designated by a black tip, so as to avoid confusion of letters.

We will now suppose that a strong magnet N is having its north pole turned towards the needles at (a), and that the latter are gradually brought closer to the magnet. In position (a) we find that the magnet N is unable to alter the relative positions of the needles; they stick stubbornly to each other. In position (b) the directing force of N has increased so much that they have been obliged to yield and to swing into new positions. The angle which they now form with the positions

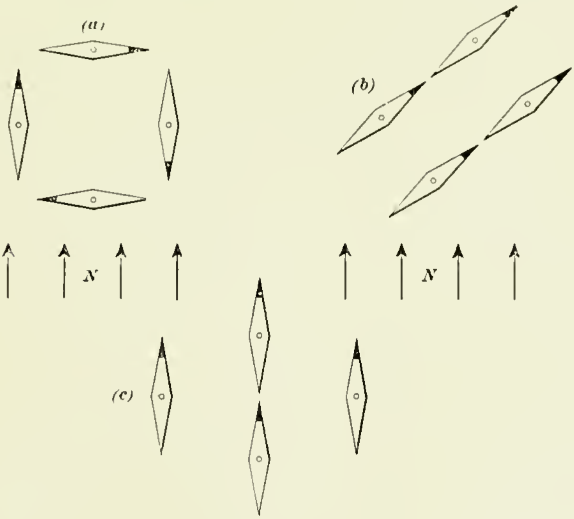

Fig. 9.

they at first occupied will increase on approaching the magnet, until suddenly they will cut loose from each other, and, after violently vibrating back and forth, place themselves in position (c). But that they are holding this position against their inclination is shown by the fact that, on removal of the magnet N, they immediately return to the first position (a).

17. Increasing the number of needles to four, the conditions are somewhat different, as there are *various* stable combinations which they now may make. Let Fig. 9 (a) represent

one such combination. It is seen that this is a very stable one, and that it will take quite an effort for the magnetizing force N to break it up. On succeeding in doing so, the needles do not yet surrender, but effect an arrangement as indicated by Fig. 9 (*b*). Finally they are compelled to also give up this combination and to submit entirely to the directing force of N, as shown at Fig. 9 (*c*).

18. Various Stages of Magnetization.—These three combinations, as shown in the last figure, illustrate very clearly, on a small scale, the three stages which have to be gone through in order to magnetize a bar of magnetic material, such as steel, for instance. There is first the *initial* stage, represented by Fig. 9 (*a*). Here it takes relatively quite an effort to effect magnetization, or to secure the required arrangement of the molecules of the iron, that is, to cause the needles to deviate from their original positions; but no sooner is the magnetizing force withdrawn than the needles at once return to their first positions. On substituting molecules in place of the needles, we come to the conclusion that on exposing the steel bar to a relatively weak magnetizing force, no lasting effects will be produced; the molecules will swing back again after the magnetization stops, and the bar will remain neutral.

19. Residual Magnetism and Saturation.—On increasing the magnetizing force until the second combination has been effected, we have gone through the second stage of magnetization, as shown at Fig. 9 (*b*). Here the molecules have succeeded in making a new and stable combination, and when now the magnet N is withdrawn, the bar will retain its magnetism, and we have passed through the stage where *residual* magnetism is effected.

If the magnetizing force is increased so as to carry us beyond this stage, we will pass through the third stage, as represented by the combination in Fig. 9 (*c*), where *saturation* takes place. But we have already seen that this, as well as the variations in the first combination, are not of a stable character. The result will therefore be that after the magnet N is withdrawn, the molecules will return to the positions occupied at the end of

the second stage, and that the magnetic strength there attained will be all that finally remains.

20. Molecular Rearrangement.—On multiplying these groups of four, we would have a combination somewhat similar to Fig. 10 (*a*), where the magnetic needles are replaced by figures which may represent molecules and on which the black tips signify north poles. We notice that the molecules are all magnetically interlocked with each other, forming stable combinations which are difficult to break. The diagram may represent a small particle of steel while in a neutal condition and exposed to a weak magnetizing force X. On increasing the latter the molecules will break their connections in order to turn around, so as to let their north poles point more in the

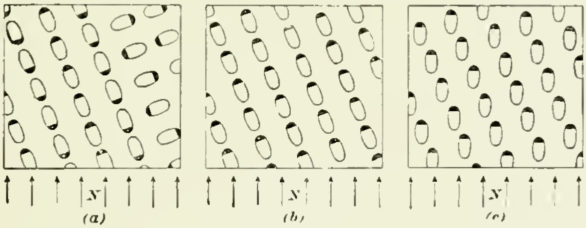

FIG. 10.

direction of the lines of force proceeding from the exterior magnet X; at the same time they will carry out new combinations of closed circuits, as shown in Fig. 10 (*b*).

A further increase of the magnetizing force will compel the molecules to again break their combinations and to stand exactly parallel with the external lines of force X, as represented in Fig. 10 (*c*); the steel is now *saturated* with magnetism. As already shown, they will not remain in these positions when magnetization ceases, but will return to the combinations of Fig. 10 (*b*), which represents *residual* magnetism.

21. Induced Magnetism.—In all the experiments so far considered, we have magnetized bars or needles by means of another magnet, without actual contact. Magnetism effected in this manner is said to be *induced*. It must now be evident from the previous explanations that no attraction or repulsion

can take place between a magnet and a neutral body made of a magnetic substance, before the molecules of that body have become arranged in the required manner—that is, not before the molecules have been compelled to break their combinations and place themselves in line with the inducing lines of magnetic force.

22. Hydraulic Analogy.—These interactions between molecules and an external magnet may perhaps be made a little clearer by an analogy from hydraulics. Let a in Fig. 11 be a short tube situated in a tank T filled with water. The tube has in its interior a propeller p constantly revolving in such a manner that it will cause the water to flow in the direction indicated by the arrows. The tube is free to revolve around the point b, and is provided with a small vane v. We may consider this as a fair representation of a molecule with its surrounding lines of force.

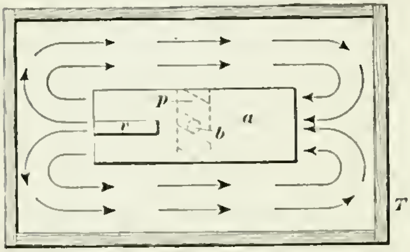

FIG. 11.

Let us place four of these tubes in a pipe P, shown in cross-section in Fig. 12 (a). They are all free to revolve around the points b, but will place themselves so as to constitute a closed circuit. Evidently there is a current constantly flowing in a circular path, from tube to tube, but there is no evidence of this outside of the tube P. We have here a condition similar to that of a piece of steel before the molecules of the steel have been rearranged by some external influence so as to exhibit the properties known as magnetization.

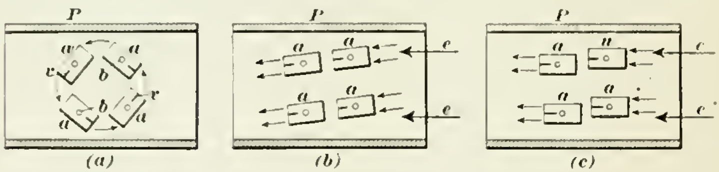

FIG. 12.

On now sending a current of water through the tube from the outside, in a direction indicated by the arrows *e* in Fig. 12 (*a*), the tendency of the current will be to deflect the tubes by means of the vanes *v* so as to send their currents in the same direction as that of the external current. If the latter is strong enough, it will be able to compel the tubes to occupy positions similar to that of Fig. 12 (*b*), which would correspond to the second stage of magnetization, where the induced magnetism is residual.

If the current-strength is increased still more, the tubes will be obliged to also give up these positions, and will then stand as in Fig. 12 (*c*), which corresponds to the condition of a saturated magnet.

When we divert the external current *e*, the tubes will return to the positions shown in Fig. 12 (*b*), and a current will now flow constantly through the tube, corresponding to the state of a substance in possession of residual magnetism. What we now have accomplished is to make an apparently neutral tube eject a constant stream of water, after first having sent an external guiding stream of water through it.

23. Examples of Magnetization.—We are now in a position to put our theories to a practical test and find an explanation for phenomena which have been familiar to us, but not understood. Let us, for instance, consider what takes place when a steel bar is being magnetized by a permanent magnet. It is an old and well-known method to stroke the bar with the magnet in a certain manner, and we are now able to see what the resulting polarity will be and why certain precautions must be taken.

In Fig. 13 we have a steel bar *B* to be magnetized by means of the bar magnet *M*. In the illustration the north pole of the bar magnet is placed at the middle of the bar and we see the lines of force proceeding from the magnet into the bar, where they divide and proceed both to the right and left, later to return to the magnet through the air. As the molecules in the bar must face with their north poles in the directions of the lines of force, we find one-half of the molecules facing in an

opposite direction to that of the other half, and we will therefore find a north pole at either end of the bar, with a south pole at the middle. A bar magnetized in this manner is said to have *consequent* poles. It is evident that matters will not be any better by moving the magnet back and forth, as the magnetism which is induced by one stroke will be reversed by the return-stroke.

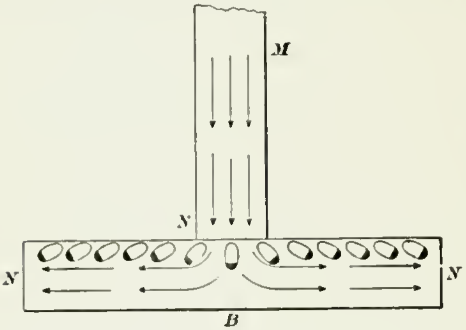

FIG. 13.

We will therefore have to change this method and proceed as indicated by Fig. 14. Here the magnet is moved from right to left, where it leaves the bar to return through the air to the starting point. During this manipulation the molecules will have placed themselves with their north poles towards the right, and their south poles towards the left, and the bar will therefore be magnetized so that its north pole is on the *right* side, and its south pole on the *left* side.

Fig. 15 proves that it is immaterial in which direction the magnet is moved, as in this instance the latter has been moving from left to right and then returned through the air. The bar has now a north pole on the *left* side. Of course, this stroking has to be repeated on the lower side of the bar.

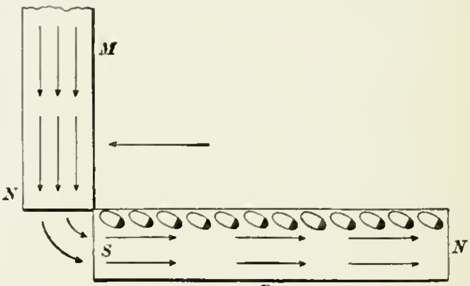

FIG. 14.

24. It will be unnecessary here to enter more into detail of the various kinds of magnetization, but, to make the examples complete, we will later on consider how magnetism may be induced by means of the electric current.

At the present stage it should no longer surprise us why, when a magnet is broken into smaller parts, each of the latter should be an independent magnet, with its own north and south pole. In fact, we can see, when looking at Fig. 14, that it should be possible to continue this breaking up of the bar into the smallest fragments and still find complete magnets of diminutive size. There is no such thing as a magnet having but one pole.

25. Effect of a Weak Inducing Magnet.—We saw, when Fig. 9 (*a*) was described, that the molecules during the initial stage of magnetization adhered rather tenaciously to one another so long as they were able to maintain their closed circuits. It would therefore appear that, if these combinations could be broken up by other means than an inducing magnet, so that the influence of the latter would simply be a guiding one, it should be possible to effect a strong magnetization with a weak inducing magnet. This has been found to be the case, and there are several methods by means of which this may be accomplished. Under these circumstances the rather weak inducing influence of the terrestrial magnetism may be used with advantage.

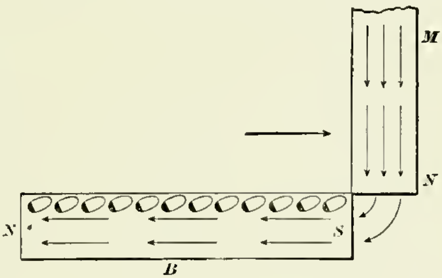

FIG. 15.

In Fig. 7 we saw the general direction of the earth's lines of force, and by means of this illustration we will be able to determine how a bar that is to be magnetized by the earth should be placed, as shown in Fig. 15, in order to be under a maximum inductive influence, and also be able to foretell the polarity of such a bar.

26. Disconnection of Molecules.—The disconnection of the molecules may be secured in four different ways. (1) *By setting the molecules into vibration.* This is accomplished by tapping the end of the bar with a wooden mallet while holding the former in a vertical position. (2) *By increasing the lateral*

distance between the molecules, which is attained by subjecting the bar to a tortional strain. (3) *By increasing the longitudinal distance between the molecules*, as effected by elongating the bar. (4) *By exposing the bar to heat*, when the result is twofold. Not alone are the distances between the molecules increased all around, but the latter are also set vibrating at a constantly increasing rate.

A bar magnetized by any of these methods will, if situated north of the equator, have a north pole at its *lower* end, because the terrestrial lines of force pass downward in northern latitudes.

THE MAGNETIC CIRCUIT.

27. Length of the Magnetic Circuit.—The *length* of a magnetic circuit represents the average lengths of all the lines of force measured from where they pass out from the north pole along their circuit through the surrounding medium to where they enter the south pole, plus their length in the magnet. *In a short bar magnet*, the length of the magnetic circuit may be exceedingly large and difficult to measure, because a great many of the lines of force will travel a long distance before entering the south pole. Whereas, *in a longer bar, bent into the shape of a horseshoe*, the lines of force pass out from the north pole and immediately enter the south pole, thus making the average length of the magnetic circuit comparatively short and easy to determine.

28. Direction of Lines of Force.—*Lines of force can never intersect each other.* When two opposing magnetic fields are brought together, the lines of force from each will be crowded and distorted from their original direction until they coincide in direction with those opposing them, and form a resultant field. The direction of the lines of force in the resultant field will depend upon the relative strengths of the two opposing magnetic fields.

29. Similarity Between Magnetism and Electricity. There are a great many points of similarity between the

flow of magnetism and that of electricity. Air is a medium that offers great resistance to both, although less to magnetism than to electricity. Magnetism will penetrate air more readily than will electricity. Metals like iron and steel are very readily penetrated by magnetism. When one of these metals is present in the magnetic circuit, the magnetic flux leaves the air almost entirely, and flows through the metal. The metallic body will then, for the time being, become a magnet with a south pole where the lines of force enter it, and a north pole where they pass out. In Fig. 16, A is a permanent magnet

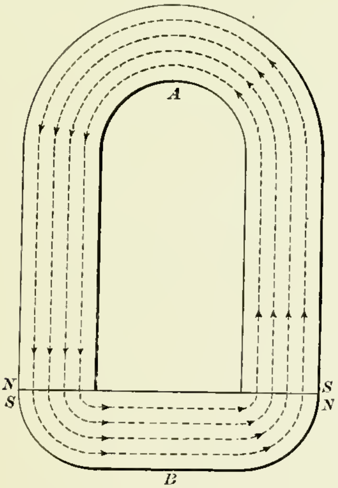

FIG. 16.

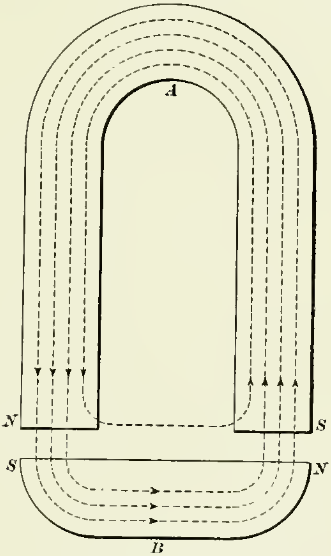

FIG. 17.

and B a piece of iron called an armature, which is placed across the poles of the magnet. The lines of force are seen to continue their path through B, making a magnet of it, while the armature in return greatly reduces the resistance of the circuit.

30. Reluctance and Magnetomotive Force.—Resistance to the flow of magnetism is called *reluctance*. Though at first glance reluctance may seem to be an exact counterpart of

the resistance of electric circuits, there is yet a great difference between them. In an electric circuit the *resistance* in ohms of a given conductor is a constant, so long as the temperature remains the same, no matter how great an amount of current may be sent through it. In a magnetic circuit the reluctance does *not* remain the same, but increases with the density of the magnetic flux, first slowly, but later on almost in direct proportion to the increase of magnetization.

When the magnetic flux is weak, the reluctance of the air may be a thousand times greater than that of iron, but when the flux is increased to a high density, the reluctance of the iron will increase until it is very nearly the same as that of air. On the other hand, we find that the flux is proportional to the force causing it to flow, here called *magnetomotive force*, and inversely proportional to the reluctance. We have, therefore, practically a parallel to Ohm's law for the electric current, and we may write the law as follows:

$$\text{magnetic flux} = \frac{\text{magnetomotive force}}{\text{reluctance}}$$

The unit of *magnetic flux* is called the *weber*; the unit of *magnetomotive force* is called the *gilbert*; and the unit of *reluctance* is called the *oersted*.

The last formula can therefore also be written in this form:

$$\text{weber} = \frac{\text{gilbert}}{\text{oersted}}.$$

31. The source of the magnetomotive force will be considered later on; at present we will consider other points of similarity between electric and magnetic currents. In an electric circuit the resistance depends on the substance of which the conductor is composed, on the length of the conductor, and its cross-sectional area; the magnetic flux is also dependent on the substance or substances that constitute the circuit, the length of the circuit, and the area of the conductor. To decrease the resistance of a wire, its length may be reduced or its cross-sectional area increased. In the same manner the reluctance of a magnetic circuit may be decreased.

The sectional area of a magnetic circuit at any point in a magnet is the area of a plane through which the lines of force pass, the plane being taken perpendicularly to the direction of the lines at that point. The sectional area of the magnetic circuit outside the magnet is an indeterminate quantity, because the lines of force spread apart and diverge in all directions before entering the south pole. But where the lines of force have only a small air-gap to pass across, the tendency to spread apart will be less, and the sectional area of the magnetic circuit may be taken as the area of the polar face. For example, the sectional area of the magnetic circuit in a bar magnet 5 inches wide and 25 inches thick is $5 \times 25 = 125$ square inches.

32. Classification of Magnetic Circuits.—There are three kinds of magnetic circuits:

1. A *non-magnetic* circuit, in which the flux has to complete the whole circuit through air, copper, or other non-magnetic materials. (See Figs. 24 and 25.)
2. A *closed magnetic* circuit, in which the flux completes its whole circuit through iron or steel. (See Fig. 16.)
3. A *compound magnetic* circuit, in which the flux passes consecutively through iron or steel and non-magnetic materials, as air, wood, etc. (See Fig. 17.)

33. Magnetic Quantity and Density.—The *amount*, or *quantity*, of *magnetism* is expressed by the total number of lines of force passing along the magnetic circuit.

Magnetic density is the number of lines of force passing through a unit area measured perpendicularly to their direction.

The length of the magnetic circuit does not affect the magnetic density in a circuit, so long as the total number of lines of force remains unchanged.

To find the magnetic density per square inch, when the sectional area of the magnetic circuit and the total number of lines of force is known:

Rule.—*Divide the total number of lines of force by the sectional area of the magnetic circuit in square inches.*

EXAMPLE.—If after measuring the magnetism in a straight-bar magnet $\frac{1}{2}$ inch square and of any length, the total amount of magnetism at the middle of the bar is found to be 25,000 lines of force, what is the magnetic density in the bar?

SOLUTION.—The magnetic density in the bar is $\frac{25,000}{.5 \times .5} = 100,000$ lines of force per square inch. This is equivalent to saying that 100,000 lines of force would pass through the magnet if its sectional area were increased to 1 square inch and the lines of force were increased in the same proportion.

MAGNETIC UNITS.

34. To facilitate a connection between the electrical and magnetic forces, a system of magnetic units has been adopted, based upon the *absolute*, or C. G. S., system of measurements, in which C. stands for centimeters, G. for grams, and S. for seconds.

A *unit magnetic pole* is one of such strength that, if placed at a distance of 1 centimeter from a similar pole of equal strength, it would be repelled with a force of *1 dyne.*

One line of force, or a *unit line of force*, is one of such strength that if a unit magnetic pole be placed upon it, the pole will be urged along with a force of 1 dyne.

A magnetic field of *unit density* is one in which every square centimeter area is cut by 1 line of force. Therefore, a magnetic field of unit density represents a condition wherein 1 dyne of force acts upon each unit pole of the magnet.

The force, in dynes, acting upon a magnetic pole placed in a magnetic field, is equal to the strength of the pole, in polar units, multiplied by the density of the magnetic field at that point.

ELECTROMAGNETISM.

35. When we considered the conditions of a magnetic molecule, it was found to be in possession of a magnetic field, or of lines of magnetic force, and the properties of magnetism and magnets, so far described, depend on the properties of these molecules with their inherent magnetism. If this were the only source of magnetism, electricity would never have been

able to reach the preeminent position it occupies today; but, happily, means for providing an inexhaustible supply of magnetism, of an intensity hitherto unheard of, were found when electromagnetism was discovered. The phenomena of electromagnetism will now be considered.

36. If a freely-supported magnetic needle is placed under a conductor in the position indicated in Fig. 18, it will, as soon as a current of electricity is sent through the conductor, turn in the direction indicated by the arrows and tend to place itself at right angles to the conductor, its angular motion depending on the strength of the current. If the *conductor* is free to move and

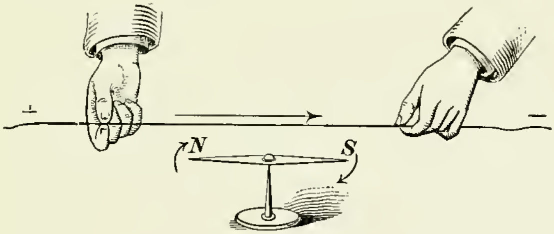

FIG. 18.

the *needle* is stationary, the conductor will move in a direction opposite to that indicated by the arrows. If both needle and conductor are free to move, the action will be mutual, each moving in a direction opposite to that taken by the other. In other words, *an electric current and a magnet mutually exert a force upon each other, and this force is always exerted at right angles.*

MAGNETIC FIELD OF ELECTRIC CONDUCTORS.

37. Magnetic Forces.—In looking for an explanation of this phenomenon, our first impulse would be to examine, if possible, the immediate neighborhood of an active conductor, to find whether the conditions existing previously have been changed since a current began to flow. On passing the conductor up through a hole in a piece of cardboard and sprinkling iron filings on the latter, we find that they will arrange

themselves in concentric circles around the wire, as shown in Fig. 19. It makes no difference if the cardboard is moved along the conductor, the effect is the same anywhere along its entire length; neither is the phenomenon limited to the immediate neighborhood of the conductor; the effect can, in fact, be traced, under proper conditions, at a distance of miles away from a conductor. A practical example of this is seen in wireless telegraphy.

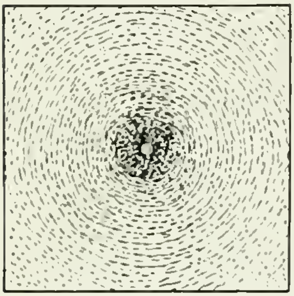

FIG. 19.

38. Magnetic Whirls.—Here we have again the lines of magnetic force, found to exist in and near magnets, but in a somewhat different form. We must imagine that the space surrounding a conductor is filled with innumerable magnetic whirls, all revolving in the same direction; these whirls are very close together near the conductor, but farther apart as their distance from the conductor increases. Fig. 20 will give a general idea of the position these magnetic whirls occupy relative to the conductor. It must be understood that part of the electric energy supplied to the conductor is utilized not

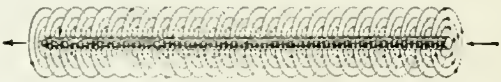

FIG. 20.

alone in setting up these magnetic whirls but also in maintaining them. If we again resort to the rubber rings as an illustration, we can understand that these whirls, like extended rubber rings, tend to counteract an attempt to extend them and enlarge their diameters, and that, after they are in an extended condition, an effort is required to maintain them in that position, their tendency being to contract themselves into the shape of small rings resting in the conductor.

To carry the illustration still further, we may suppose that an

increase of current-strength will result in an increase of the diameter of the existing circular lines of force at the same time that new lines of force will be sent out from the conductor, the result being that there will be an increase of whirls per unit length. The *starting* of a current will therefore be followed by a spreading out of these whirls; while, on the other hand, the *stoppage* of the current will result in an immediate return of all the whirls to their original starting place in the conductor.

39. Direction of Magnetic Whirls.—It was stated above that these magnetic whirls were all revolving in a certain direction; it must here be added that the direction of the current in the conductor always stands in a certain relation to the direction in which the magnetic whirls rotate, so that by knowing the direction in which one of the two factors is moving, the direction of the other can always be determined. Considering these whirls as made up of circular lines of magnetic force, we can now see why the active conductor should have an influence on the magnetic needle, as was shown to be the case by means of Fig. 18, and it now remains to find in which direction the lines of force are moving when the current in the conductor is flowing in various directions.

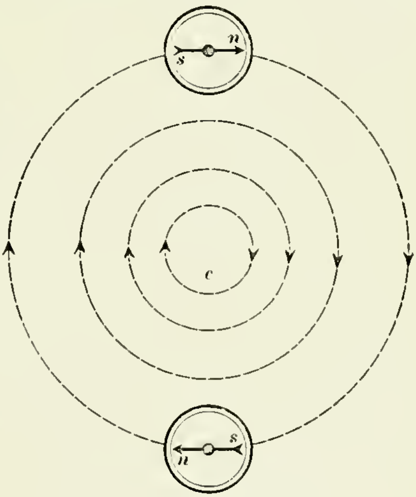

FIG. 21.

If we imagine a current to be flowing from the observer towards and into the conductor c, Fig. 21, it will be found that the lines of force travel in the direction indicated by the arrows, and as the magnetic needle always points with its north pole in the direction in which the lines of force are traveling, it follows that a magnetic needle, if placed above the conductor, would

point to the right, and if below to the left. From this we deduct the following:

Rule.—*If the current in a conductor is flowing away from the observer, then the direction of the lines of force will be around the conductor in the direction of the hands of a watch.*

A simple method for remembering the connection between the lines of force surrounding a conductor and the direction of the current in the latter, is the following: Imagine an ordinary nut *a*, Fig. 22, to represent the lines of force, and a bolt *b* to be the conductor, both nut and bolt having, as usual, a right-hand thread. If the bolt is placed with its head *c* downwards and the nut screwed on the bolt, it will turn towards the right and will at the same time move downwards. The direction in which the nut revolves gives the direction of the lines of force, and the direction in which the nut proceeds indicates the direction of the current. It follows that, should the current be reversed, the lines of force will run in an opposite direction.

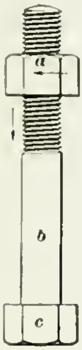

FIG. 22.

40. Attraction and Repulsion of Lines of Force. The rule, given in Art. **10**, stating that lines of force, when

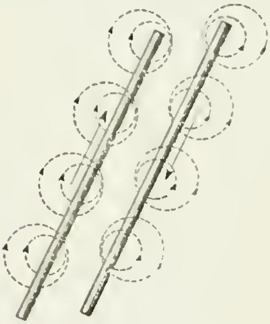

FIG. 23.

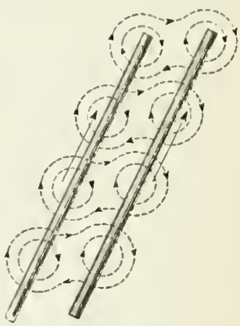

FIG. 24.

running in the same direction, repel one another, and when running in opposite directions attract one another, also holds

good for a magnetic field surrounding an active conductor. Let us examine the effect of these attractions and repulsions on two parallel conductors with the currents in them running in opposite directions and placed near each other, as in Fig. 23. Examining the few isolated whirls there represented, we find the lines of force adjoining each other to be running in the same direction; a repulsion will therefore take plaee. The whirls tend to crowd together near their respective conductors, and as these whirls are supposed to be elosely interlinked with the molecules of the eonductors, a mutual repulsion of the lines of force will result in a mutual repulsion of the two conductors.

On the other hand, if, as in Fig. 24, the currents in both conductors run in the same direction, the lines of force adjoining eaeh other are found to run in opposite directions; they will therefore mutually attract each other and unite into one line, and as the tendency of each line is to contract itself, the result will be that all the lines of force will seek to draw the conductors eloser together; that is, an attraction will take place.

From these experiments we deduct the following law, as first expressed by Ampere:

Rule.—*Two parallel portions of a circuit attract each other if the currents in them are flowing in the same direction, and repel each other if the currents flow in opposite directions.*

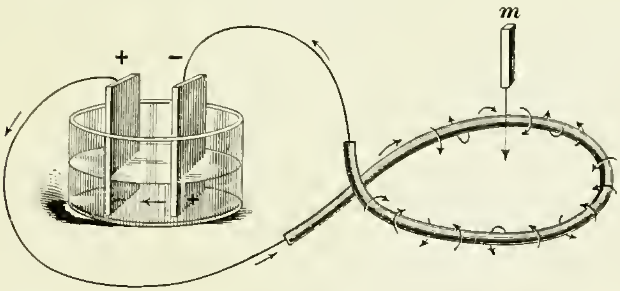

FIG. 25.

If the conductor carrying the current is bent into the form of a loop, as shown in Fig. 25, then all the lines of force around the conductor will pass through the loop in the same direction.

Any magnetic substance, therefore, such as *m*, when placed in front of the loop, would tend to place itself with its longest axis projecting into the loop—that is, in the direction of the lines of force.

41. Solenoid.—It can be easily seen now that by increasing the number of loops, as in Fig. 26, the lines of force of each loop will join into one long loop, enclosing all the conductors, and entering at one end will pass through the whole *helix* to make a return path on the outside. In fact, we find the same conditions that exist in a bar magnet—the lines of force pass out from one end and enter at the other; by closer examination the solenoid is also found to possess a north and a south pole, and will magnetize and attract magnetic bodies. It will also, if freely suspended, place itself in the direction of the magnetic meridian. A helix made in this manner and with a current of electricity flowing through it, is called a *solenoid*. A helix always has a penetrable interior; a magnet, never.

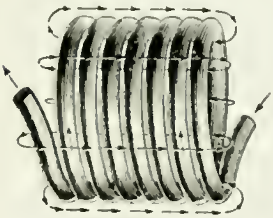

FIG. 26.

42. Direction of Current Around Solenoid.—To determine the direction in which the current will have to circulate around a solenoid, in order to produce a north or a south pole on the end nearest the observer, we may again utilize the rule stated in Art. **39**, giving the direction of the lines of force in an active conductor.

This is purposely done in order to limit the rules requiring memorizing to the fewest possible, and to so connect these rules that they may all be derived from one main rule, if it should occasionally be found necessary to refresh the memory.

In the rule referred to, it was said that the direction of the lines of force around a conductor are in the direction of the hands of a watch, when the current flows away from the observer. If we now reverse the conditions and place the lines of force where the current was, and let the current circulate instead of the lines of force, we have the following modification of the previous rule.

(*a*) **Rule.**—*If the lines of force are flowing into a helix away from the observer, then the direction of the current around the helix will be in the direction of the hands of a watch.*

When the direction in which the current circulates is known, then the rule may be stated in the following form :

(*b*) **Rule.**—*If the direction of the current around a helix is in the direction of the hands of a watch, then the lines of force are flowing into the helix away from the observer.*

We have already seen that in a magnet the lines of force enter at the south pole and leave at the north pole ; therefore, when looking at the end of a helix *into* which the lines of force are flowing, we are looking at its south pole. If we are looking at a north pole the current will circulate in a direction *opposite* to that of the hands of a watch.

43. Ampere-Turns.—When the *magnetomotive force* was mentioned in the previous pages, the source of it was left an open question ; it will now be seen that the magnetomotive force depends for its strength on *the intensity of the current and on the number of coils, or complete turns, through which the current passes.* The total number of turns multiplied by the strength of the current in amperes will give the magnetizing force in *ampere-turns.* It has been proven that, for a given number of ampere-turns, it is of no consequence what relation the two factors, amperes and turns, have to each other, so long as their product remains the same. For instance, it is immaterial whether 500 ampere-turns are produced by 100 amperes circulating through 5 turns, or 5 amperes through 100 turns, so long as their product remains 500. *An ampere-turn is defined as the amount of M. M. F. produced by a turn of wire carrying 1 ampere.*

44. Permeability.—It was seen in Art. 28 that, when a magnetic substance is brought into a magnetic field, the lines of force in the field crowd together, and all try to pass through the substance ; in fact, they will change their curved shape, as seen in Fig. 16, and go a considerable distance from their original

position in order to pass through it. *A magnetic substance, therefore, offers a better path for the lines of force than air or other non-magnetic substances.*

The facility afforded by any substance to the passage through it of lines of force is called *magnetic permeability*, or simply *permeability*.

The permeability of all non-magnetic substances, such as air, copper, wood, etc., is taken as 1, or unity. The permeability of soft iron may be as high as 2,000 times that of air. This is one of the reasons why soft iron is used as a core in the solenoid of the faradic apparatus. If, therefore, a piece of soft iron be inserted into the magnetic circuit of a solenoid, the number of lines of force will be greatly increased, and the iron will be magnetized.

ELECTROMAGNETS.

45. A magnet produced by inserting a magnetic substance in the magnetic circuit of a solenoid is an *electromagnet*, and the magnetic substance around which the electric current circulates is called the *core*, as shown at *C* in Fig. 27. The north and south poles would be as indicated, for reasons already given.

46. Permeability and Conductivity.—It may make matters a little clearer to compare the permeability of a magnetic substance with the conductivity of an electric conductor. With a given electromotive force, the strength of the current in a wire depends on its conductivity. If a wire of less resistance, or higher conductivity, is used, the current-strength will immediately increase in direct proportion to the conductivity. The behavior of a magnetic circuit in a solenoid is somewhat similar. Let a given number of ampere-turns produce a magnetic flux of a certain density; if the resistance of one part of the circuit be decreased by inserting a piece of soft iron in the solenoid, the magnetomotive force will have less resistance to overcome, because the iron is a better magnetic conductor than air and is of a higher magnetic permeability; the result, therefore, will be a corresponding increase in the magnetic flux. It is well to bear in mind that here the similarity ceases,

as the permeability is not a constant quantity, like the resistance of a conductor, but varies with the density of the flux.

47. Magnetizing Coil of an Electromagnet.—In an electromagnet, as ordinarily constructed, the magnetizing coil consists of a large number of turns of insulated wire; that is, wire covered with a layer or coating of some non-conducting or insulating material, usually silk or cotton; otherwise, the current would take a shorter and easier circuit from one turn to the adjacent one, or from the first to the last turn, through the iron core, without circulating around the magnet.

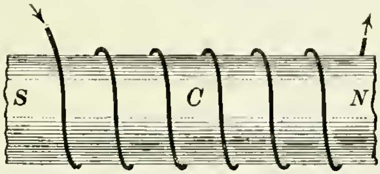

FIG. 27.

An electromagnet in its simplest form is shown in Fig. 27, and as it is usually constructed in Fig. 28. Though the efficiency of an electromagnet in this form is rather low, it has been used to a very large extent in therapeutics as an induction-coil. It consists of a straight bar of iron or steel B fitted into a spool or bobbin $C C'$ made of hard vulcanized rubber or some other inflexible insulating material. The magnetizing coil of fine insulated copper wire w is wound in layers on the bobbin, as shown.

48. Polarity of an Electromagnet.—The rule given in Art. **39** determines the polarity of a solenoid when the direction in which the current is flowing is known. The same rule holds good for an electromagnet, and it makes no difference towards which end it is wound, whether wound in one layer or in any number of layers, as long as it is always wound in the same direction around the spool. The main point to observe is that the current shall circulate throughout the coil, always in the *same direction;*

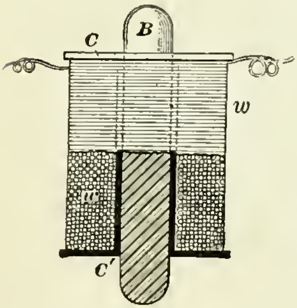

FIG. 28.

as, for instance, in the direction of the hands of a watch. Should the inner layers be wound in a direction opposite to that of the outer layers, there would be a tendency to produce a north pole and a south pole at the same end of the magnet, with the result that the magnetizing forces in each layer would neutralize each other; hence the iron core would not become a magnet.

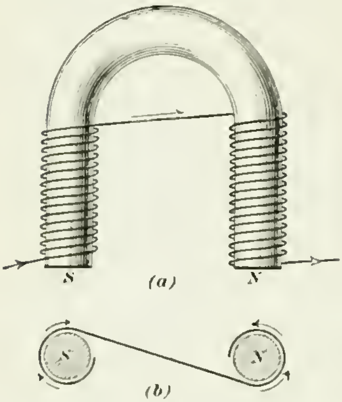

Fig. 29.

49. The Horseshoe Electromagnet.—A form of electromagnet much more efficient than that shown in Fig. 28, and one which is put to a greater variety of uses, is the *horseshoe*, or **U**-*shaped*, electromagnet, illustrated in Figs. 29 and 30. It consists of a bar of iron bent into the shape of a horseshoe, with straight ends, and provided with two magnetizing coils, one on each end of the magnet; the two ends, which are surrounded by the magnetizing coils, are the *cores* of the magnet, and the arc-shaped piece of iron joining them together is known as the *yoke* of the magnet. The ordinary **U**-shaped magnet, shown in Fig. 30, is made in three parts; namely, two iron cores M wound with the magnetizing coils c, and a straight bar of iron b joining the two cores together. In looking at the face of the two cores, Fig. 29 (b), and remembering the rule which gave the relation between the polarity and the direction of the current flow, it is seen that the current must circulate in opposite directions around the two cores, otherwise they would both be of the same polarity. If the rules already given have been carefully studied, the

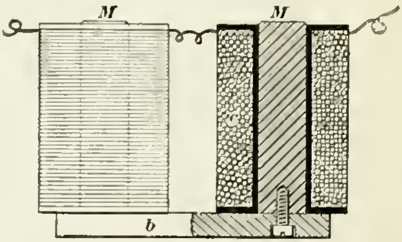

Fig. 30.

reason for winding the two cores of this magnet in opposite directions will be easily understood.

Following the path of the magnetic flux in Figs. 28 and 29 (*a*), it can easily be seen why the latter should be the more efficient of the two. In Fig. 28, the return-path of the lines of force lies along the whole length of the bar *B*, and, being through air, must necessarily be of high resistance. In Fig. 29 (*a*), the lines of force have simply to cross over the gap between *N* and *S*, while the rest of the circuit is completed through iron. Bringing the poles closer together would decrease the resistance still more.

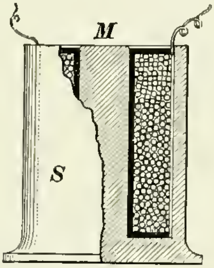

Fig. 31.

50. The Iron-Clad Electromagnet. The electromagnet of the least resistance is the one known as the *iron-clad* electromagnet, and illustrated in Fig. 31. It contains only one magnetizing coil and one core. The core *M* is fastened to a disk-shaped yoke and the magnetic circuit is completed through an iron shell *S* that rises up from the yoke and completely surrounds and protects the coil. If an armature is placed in front of the core, the paths of all the lines of force will be through iron.

ELECTROMAGNETIC INDUCTION.

51. Electromotive Force in a Conductor.—It has been shown that a magnet is constantly surrounded by a field of magnetic force, and also that the surrounding space of a conductor is immediately filled with circulating lines of force, as soon as a current begins to pass through it. Further on it was shown that the lines of force surrounding two or more magnets or two or more conductors react on each other; that is to say, not alone magnet on magnet, but also magnet on conductor. On observing the phenomenon that lines of force begin to move around a conductor on the closing of the circuit, the question might perhaps suggest itself as to whether a reversal of the phenomenon was possible; or, in other words, whether lines of

force could be made to create an electromotive force in a conductor and start a current. Faraday made the important discovery that this effect is indeed produced in a conductor under the conditions mentioned, and thus laid the foundation of the principles on which the dynamo of today is based.

In the following pages we will therefore consider the other methods mentioned in Art. **21**, *Direct Currents*—those producing an E. M. F. by means of dynamo-electric machines, induction-coils, etc. In either of these appliances it is a question of interaction between magnetic lines of force and electric conductors and of producing a motion of the lines of force or of the conductors, as the case may be.

52. This interaction between magnetic lines of force and a conductor can be shown by means of the following apparatus: In Fig. 32 *(a)*, *a* is a solenoid, whose terminal wires *c* and *d* are wound a number of times around the compass *e*, which then serves as a *galvanometer*, an instrument described in *Essential Apparatus*. From the explanation given in Art. **36**, it is clear that if a current is passing through the wires *c* and *d* it will affect the compass and compel it to swing either to the left or right, depending on the direction of the current. If, now, the magnet *b* is moved quickly into the interior of the solenoid. the compass needle will swing through a certain angle, proving that a current has been passing through the solenoid. As soon as the magnet stops its motion, the needle will swing back to its initial position and come to rest.

When, now. the magnet is withdrawn from the solenoid, the needle will again swing through a certain angle, but in an opposite direction to that of its first deviation, proving that in this instance again a current was started, but in an opposite direction to the former current.

It will also be found that no current is flowing so long as the magnet remains stationary, but only when a change takes place in the position of the magnet. The quicker these motions are, the more will the needle deviate, and, consequently, the stronger the actuating current must have been. Of course, the same

effects will be produced if the magnet is stationary and the coil constitutes the moving part.

53. A Solenoid Conveying a Current Acting as a Magnet.—On replacing the magnet by another solenoid *b*, as in Fig. 32 (*c*), the results will be similar; on letting *b* enter the solenoid *a*, a current will flow through the latter in an opposite direction to that of the other current, which is established by the removal of the solenoid *b*.

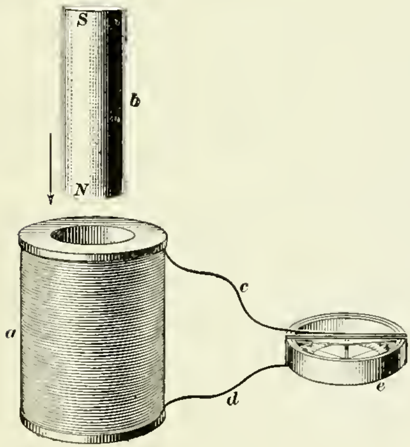

Fig. 32 (*a*).

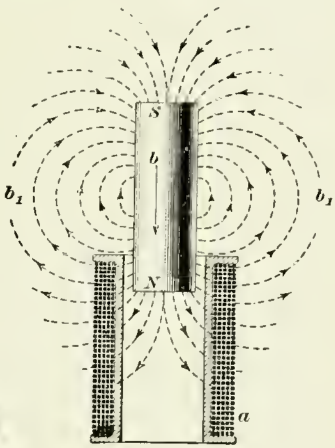

Fig. 32 (*b*).

It is further found that if this solenoid conveying a current is placed inside another solenoid, and the circuit of the former *broken*, a current will flow in this latter solenoid as if the solenoid conveying a current had been suddenly withdrawn. Likewise is it found that on again *closing* the circuit the effect on the solenoid not conveying a current will be the same as if the solenoid conveying a current had been reinserted. In fact, any weakening or strengthening of the current in the solenoid conveying a current has the same effect as if the coil was approaching or receding from the solenoid conveying no current.

We see, then, that a current is flowing through the coil *a* *only* when one of the coils moves relatively to the other, or when the strength of the current in the active coil is changing. As long as both coils remain stationary, or the current in the active coil does not vary in strength, *no* current will flow in the coil in which a current is to be induced.

That, in these experiments, the magnet *b* and the active coil *b* both have the same effects on the coil in which a current is to be induced should not be surprising, as it was shown in Art. **41**, and by means of Fig. 26, that a solenoid possesses

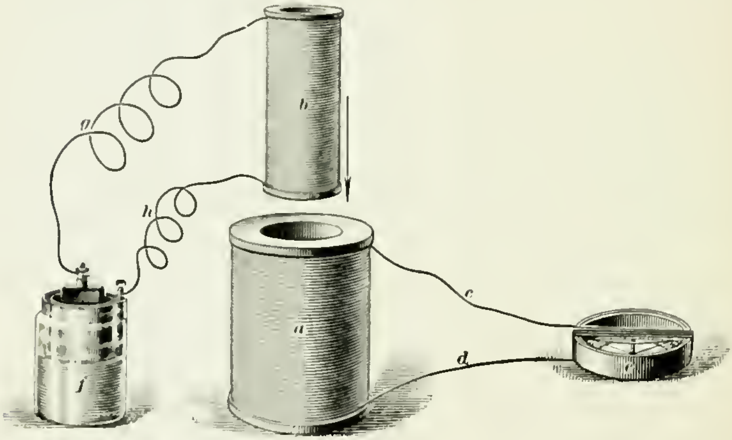

FIG. 32 (*c*).

lines of force which flow through and around it in the same manner as those of a permanent magnet.

In looking for an explanation of these phenomena we will have to investigate the actions of magnetic lines of force on a conductor, when the latter is in motion relative to the former.

In Fig. 32 (*b*), the coil *a* in which we wish to induce a current is shown in cross-section, and the magnet *b* is surrounded by dotted lines b_1, indicating the position and direction of its magnetic lines of force. We see these lines of force pass through the surrounding copper wires without being diverted from their course, and as if these wires did not exist. If, now,

the magnet is moved downwards, these lines of force will pass across the various turns of wire in the coils, and a certain interaction between the conductor and the lines of force will take place, whereby an electromotive force is created in the coil. There will then be a tendency to start a current, and if the circuit is closed, as in Figs. 32 (*a*) and (*c*), a current will flow in the coil and show its presence by its action on the compass *e*.

54. Direction of Induced E. M. F.—We will now have to consider this interaction between a conductor and lines of force more in detail and find some rule that will indicate in which direction the induced E. M. F. tends to act, when the lines of force are flowing in a given direction.

The principle according to which this interaction takes place may be stated as follows : *A conductor, moving across a magnetic field so as to cut the lines of force, will have an electromotive force produced in it, and the direction of this E. M. F. in the conductor will depend on the relative directions of the magnetic flux and the motion of the conductor.*

Fig. 33 will make this principle clearer. The lines of force are here passing from the north pole *N* of a horseshoe magnet, and through the air-gap in the direction indicated, to the south pole *S*. The conductor *A*, shown in cross-section, is moving across the field in the direction of the arrow, and an electromotive force will now be produced in the conductor, which tends to send a current through the same downwards, through the paper. It is seen that the current will then flow in a direction at right angles to the direction of the lines of force and also to the direction of motion. If the motion of *A* is reversed, the current will pass upwards away from the paper.

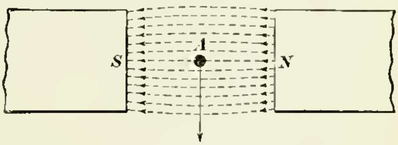

FIG. 33.

It is important that this principle be well understood, as by its means all phenomena connected with electricity in motion can be easily explained and analyzed in all their variations. Many rules have been suggested by means of which to make

the direction of the induced currents more easy to remember. The one suggested by Dr. Fleming is as follows :

Rule.—*Hold the thumb and the first and the middle finger of the right hand as nearly as possible at right angles to each other, as in Fig. 34, so as to represent three rectangular axes in space. If the thumb points in the direction of the motion, and the forefinger along the direction of the magnetic lines, then the middle finger will point in the direction of the induced electromotive force.*

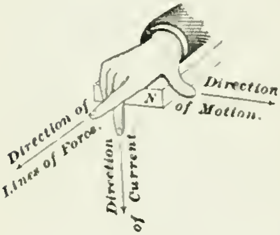

FIG. 34.

Also, the following adaptation of Ampere's well-known rule is frequently used.

Rule.—*Imagine a swimmer to be floating along a conductor and that his face is turned in the direction in which the lines of force are moving. If both the swimmer and the conductor are moved towards his right hand, the direction of the electromotive force induced by this motion will be from the feet to the head of the swimmer.*

35. The following rule, suggested by the writer, has been found very easy of application :

Rule.—*Imagine a triangle B, Fig. 35 (a), placed on a table with its high side to the right, and let a pencil A be held against its upper edge. Suppose, now, that the lines of force are passing from the observer's eyes and proceeding towards the triangle, and that the pencil be moved to the left. When it reaches the point of the triangle, it will, in addition to its lateral motion, also have made a downward motion, indicating that the electromotive force produced in the conductor tends to send a current in a downward direction. By moving the conductor towards the right, the reverse will take place; i. e., the current will tend to flow upwards.*

After this explanation, Fig. 35 (*b*) alone will be sufficient to determine the direction of the induced electromotive force by merely imagining the lines of force to proceed from the

observer's eyes towards the paper, so that when the pencil moves in the direction indicated, the direction of the induced electromotive force will be towards the bottom of the page.

It is well to call attention to the fact that in the rule just given, no mention has been made of a current flowing; it has simply been said that the electromotive force tends to act in a certain direction, and that it will continue to act so as long as

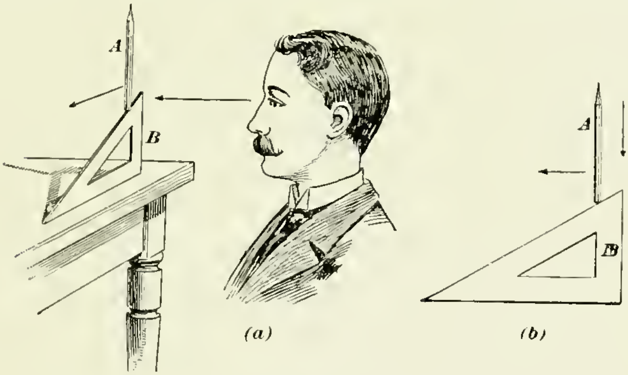

Fig. 35.

the conductor continues to cut across the lines of force. Whether or not a current will flow depends upon the condition of the circuit. If the circuit is closed a current will flow; if it is open no current will flow.

56. Magnitude of the E. M. F.—The *magnitude* of this E. M. F. will depend not only upon the number of lines of force cut through, but also upon the *rate* at which they are cut. If the conductor passes very rapidly through the magnetic field, the E. M. F. will be very high, but not of long duration, while a slow passage through the field will produce a weak E. M. F., but one sustained correspondingly longer.

57. Absolute Unit of Potential.—*One absolute unit of potential* is the potential produced in a conductor when it is cutting lines of force at the rate of *one line of force per second.*

By definition, *1 volt* is equal to 100,000,000, or 10^8, absolute units; consequently, in order to produce an electromotive

force of 1 volt, the *rate of cutting* must be 10^8 lines of force per second. This can also be expressed algebraically; thus,

$$E = \frac{N}{10^8 \times t},$$

where E = electromotive force in volts;
N = total number of lines of force cut by the conductor;
t = time in seconds taken to cut the lines of force.

If the total number of lines of force remains unchanged, it will make no difference in the electromotive force developed, whether the lines of force proceed from a permanent or from an electromagnet.

58. Cutting Lines of Force.—According to Ohm's law, the current obtained from conductors cutting lines of force is equal to the quotient arising from dividing the total electromotive force generated by the total resistance of the circuit through which the current passes. In general, the total resistance is the resistance of the conductor cutting the lines of force, or the resistance of the *internal* circuit, plus the resistance of any conductor or conductors that complete the *external* circuit. If E represents the total electromotive force in volts, r and R the resistance in ohms of the internal and external circuits, respectively, and C the current in amperes, then $C = \frac{E}{R + r}$.

59. Limit of Induced E. M. F.—It will be seen from the above expression that either a large or a small induced current can be obtained from conductors cutting lines of force by simply changing the combined resistance of the internal and external circuits. There is, however, a maximum limit to the amount of current obtainable in this manner. The lines of force, which are produced around the conductor by the current itself, will always act in opposition to those producing the electromotive force, and will tend to distort or crowd them away from their original direction. The number of lines of force produced around the conductor by the current, is directly

proportional to the strength of the current, and consequently, as the current becomes larger and larger, the lines of force which are being cut by the conductor become more and more distorted and crowded away from their original direction, until the conductor is no longer able to cut all the lines of force, and therefore the generated electromotive force becomes smaller. A means generally employed to get rid of this effect is to make the density of the magnetic field large in proportion to the current. This interaction between the lines of force around the conductor and the lines of force cutting the conductor also explains why it becomes more and more difficult to move a conductor through a field as the field grows stronger, as in a large dynamo, and why it requires hundreds of horsepowers to turn an armature, which, when the dynamo is at rest, may be turned by hand.

Fig. 36 shows that the direction of the lines of force on the front of the moving conductor is such that a mutual repulsion will take place between them and the lines of force of the stationary field, tending to push the conductor in a direction contrary to the one in which it is moving; while, on the other hand, the lines of force on the rear of the conductor exert an attraction on the cutting lines of force, and seek, like the lines in front, to prevent the motion of the conductor. This reaction may be compared with the resistance which the air exerts on an oscillating fan; an increase in speed will be met with an increased resistance; while on the cessation of motion the resistance will vanish altogether.

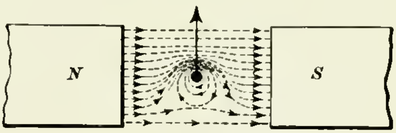

Fig. 36.

60. Stationary Conductors and Moving Fields.—It must not be supposed that, in order to produce an electromotive force in a conductor, it is necessary for the latter to move, and that the magnetic field must always remain stationary; on the contrary, the fact is that the opposite case, that of the stationary conductor and a moving field, is a combination as frequently

met with in regular practice. The millions of telephones in use are examples of stationary conductors and moving fields, and, to quote a few other instances, so are the transformers and induction-coils. It makes no difference which one of the two elements is in motion so long as the cutting of lines of force takes place. It is no matter whether both are moving in opposite directions or whether both are moving in the same direction with a different speed, with the result that there is a relative motion between them. The rule illustrated by Fig. 35 holds good in either case; it is only a question of determining the direction of the relative motion between the two elements; but should it be desirable to apply the rule directly to the case of a moving field and a stationary conductor, then simply move the triangle in the direction of the moving field, while the pencil is allowed an up-and-down motion only. The direction in which it is moving will then be an indication of the direction in which the electromotive force is acting.

VARIOUS MEANS FOR INDUCING AN E. M. F.

61. Classes of Induction.—All these various combinations of moving magnetic fields and conductors are usually classed under the following four headings: magneto-electric induction; electromagnetic induction; mutual induction; self-induction.

It would perhaps have been more correct to place the self-induction and mutual induction first, but as these subjects are more easily comprehended when an explanation has been given of the magneto-electric induction, they have been arranged in the above order.

62. Magneto-Electric Induction.—In magneto-electric induction, an electromotive force is induced in a conductor by moving it across a magnetic field or by passing a magnetic field near a conductor; it is immaterial which is done so long as a relative motion between the conductor and the magnetic field takes place. It has already been described, in Art. 52,

how the cutting of lines of force affects a conductor and the direction in which the E. M. F. is acting; it now remains to show the application of the law. In Fig. 37, *A* is a permanent magnet with its north pole at *N* and its lines of force proceeding in the direction of the arrows; *C* is a coiled conductor shown in cross-section, that portion of the coil which is cut away being indicated by dotted lines. If the magnet is moved towards and into the coil in the direction indicated by the arrows, the conductor will cut lines of force, and an E. M. F. will be produced in the coil. Let us, by means of Fig. 35 (*b*), try to determine the direction in which this E. M. F. is acting. Considering only that portion of the coil marked *B*, and looking at it in the direction of the lines of force, we see that the lines of force are moving towards the left-hand side of the coil. Therefore, moving the triangle in Fig. 35 (*b*) also to the left, it is observed that the pencil moves upwards; the E. M. F. in the part *B* is therefore also acting in an upward direction. Looking into the coil from the end where the magnet enters, the current will circulate in the coil in a counter-clockwise direction, and the right-hand end of the coil must be a north pole. As it is known that similar poles of magnets repel each other, the coil will tend to prevent the entrance of the magnet. If, on the contrary, the magnet is moving out of the coil, the direction of the current will be reversed and the right-hand end of the coil will then be a south pole; consequently, an attraction will take place between magnet and coil; hence, the latter is seeking to prevent the removal of the magnet. These effects take place *only* when the magnet is in *motion;* as soon as the motion ceases the current stops. We have here a confirmation of the experiment illustrated by means of Fig. 32 (*a*). Upon this action of a magnet on a coil, the following rule, called Lenz's law, has been based.

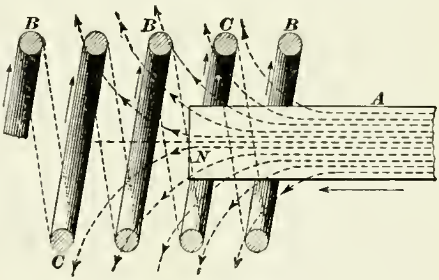

Fig. 37.

Rule.—*When a conductor is moving in a magnetic field a current is induced in the conductor in such a direction as by its mechanical action to oppose the motion.*

63. Electromagnetic Induction.—In electromagnetic induction, the magnetic field is produced by an electromagnet instead of a permanent magnet, as shown in Fig. 32 (*c*); otherwise the conditions are the same. This combination is illustrated in Fig. 38, in which *A* again is the moving magnet (here a solenoid) in which the current circulates in the direction indicated by the arrows. The stationary coil *C* is here shown in cross-section with the upper part indicated by dotted lines. The cutting of lines of force will affect the parts *B* in the same manner as before, and the current in the parts marked *B* will therefore be in the direction of the arrows. Comparing the direction of the currents in the two coils, it will at once be seen that they are flowing in *opposite* directions, and, from the previous experiment, we will come to the conclusion that when *A* is retreating, they will move in the *same* direction. As it has already been demonstrated that parallel conductors repel each other when their currents run in opposite directions, and attract each other when they run in the same direction, it can at once be seen that the coil *C* opposes both the advance and retreat of the coil *A*. The magnetic flux started by the coil *C* is in a direction entirely opposed to that of the coil *A*, and its tendency is to diminish the flow of the latter, and therefore also to diminish the strength of the current in the coil *A*. Applying Lenz's law to this phenomenon, we may sum up the matter by saying that *in all cases of electromagnetic induction the induced currents have such a direction that their reaction tends to stop the motion which produces them.*

64. Mutual Induction.—The mutual induction is in reality only a modification of the electro-magnetic induction. We observed before that it was immaterial whether the conductor or the magnetic field was moving, so long as the lines of force were cut by the conductor. We may therefore go a step further and imagine the coils in Fig. 38 as stationary, and by some means impart a motion to the magnetic field; a current

should then be started in the coil C. The only question would be how to move the magnetic field of the coil A without moving the coil itself.

Art. 38 stated that an increase in current-strength was followed by an increased number of lines of force encircling the conductor, and also by a spreading of the same; that is to say, the magnetic whirls could be supposed to increase their diameters. Illustrating these motions more fully by means of

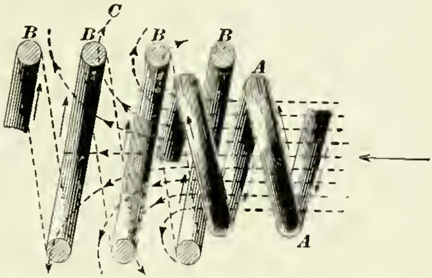

FIG. 38.

Fig. 39, we may imagine a current of a certain strength to be flowing through the coil A, and that the lines of force a, a, a are produced by the same. If, now, the voltage and strength of the current were increased, the lines of force would move forward to the left until they occupied the position of lines a', a', a' This motion would be equivalent to a motion of the whole coil A, and would be accompanied by the same result—that is, the starting of a current in an opposite direction. The tendency of the induced current will be to again send an opposing magnetic flux through the inducing coil and thus diminish the flow of both magnetism and electricity. As long as the strength of the current in the coil A is constant, the lines of force circulating around it will remain in the same position, and there will be no current in the coil C; it is only while changing their positions that forces tending to counteract these changes begin to work. A decrease or stoppage of the current in coil A is followed by a retreat or a complete collapse of its lines of

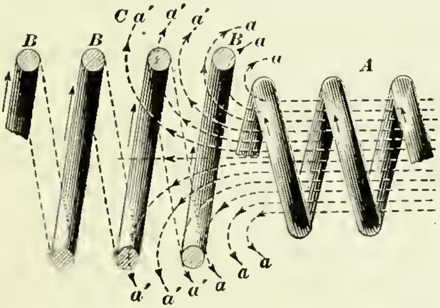

FIG. 39.

force; and, as the latter now have to move across the conductor B in an opposite direction, the induced current will also have changed its direction to one corresponding with that of the inducing current. As a consequence of this, the induced current tends to start a magnetic flux in the same direction as that of the coil A, striving to keep up its flow and prevent its decrease and stoppage. A is usually called a *primary* and C a *secondary* coil.

65. Self-Induction.—The phenomenon of self-induction may be considered as a case of mutual induction. Let Fig. 40 represent a combination of five conductors projecting through the paper; when a current is sent through the conductor A in a downward direction, the lines of force a will circulate in a direction indicated by the arrows. As long as the current-strength remains constant no effect is noticeable in the conductors B, but an increase in its strength will immediately be

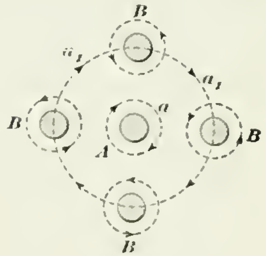

FIG. 40.

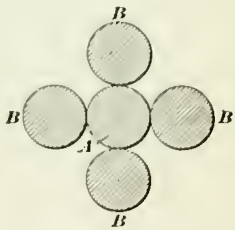

FIG. 41.

followed by a spreading of the lines of force into a position a_1, and a cutting of the latter by the conductor B. The result will then be the creation of electromotive forces in the latter which will send a current upwards, and, therefore, in a direction contrary to that of the current in conductor A. A stoppage of the inducing current will of course be the cause of reversing the currents in conductor B so that they now will flow in the same direction as that of A. Let us now apply these results to an explanation of self-induction, by placing all the conductors in contact with one another; therefore, in reality, constructing one large conductor out of several smaller ones. Fig. 41 represents such a combination. Of course it is at once

seen that sending a current through A only will again be accompanied by results corresponding to those indicated in Fig. 40; but, in the present instance, we have to imagine that the conductors B also are carrying a current, and that all of the conductors are subjected to mutual induction. The effect will be that every conductor will tend to stop the current flow in the surrounding conductors. On the other hand, when the current is decreasing or stopping, all the returning lines of force of each conductor will have a tendency to maintain the current in its neighbors. It is not necessary that a conductor should be made up of several independent conductors in order to be under the influence of self-induction. On the contrary, we can imagine any solid conductor to be made up of numerous smaller ones, all influencing one another in the manner just described. We must therefore come to the following conclusions: *That any conductor tends to oppose the passage of a current through it by setting up an electromotive force acting in opposition to that of the current; and further, that after a current is flowing, the conductor tends not alone to prevent an increase, but also a decrease of same.* This opposing E. M. F. is also called a *counter-electromotive force.*

66. Extra Current.—A decrease or stoppage of the current is, as previously shown, accompanied by a vanishing of the lines of force from the space surrounding the conductor; the lines of force belonging to the various parts of the conductor will therefore tend to maintain the current and will prevent a sudden decrease or stoppage of the latter. These induction effects are called *self-induction;* they are always present whenever a current begins to flow in a circuit, also when its strength varies and when it stops. As soon as the circuit is closed, the current should at once attain its full strength; but it does not. Some little time is required, during which the magnetic flux around the conductor is constantly increasing in strength. We have seen that the cause of this is the setting up of an electromotive force, called *counter-electromotive force,* because it is acting in opposition to the impressed electromotive force. Again, it is noticed that when a circuit is suddenly broken, there appears a

minute spark at the point of opening. This is because the self-induction of the circuit at this moment is very great, the lines of force closing up with great rapidity, and therefore a high induced E. M. F. is generated in the same direction as the impressed E. M. F., thus causing a strong current to flow. This current is called an *extra current*. This *extra current* is always produced when the circuit is broken. In a straight conductor its effects are not so noticeable; but if the conductor be formed into a coil, and provided with an iron core, then, on opening the circuit, there will be a brilliant spark, and a person holding the two ends of the wires between which the circuit is broken, may receive a slight shock, owing to the high E. M. F of this self-induced or extra current.

67. In the previous explanation of induction, the action of the lines of force has been gone into in some detail, as otherwise the phenomena could not very well be understood. Ordinarily, such a detailed examination will not be necessary, although it is well to be in possession of the means required for such investigations. When it comes to the action of a magnet entering a coil, or the mutual induction of two coils in proximity to each other, it is sufficient to remember the rule given in Art. **63**, that a conductor moving in a magnetic field has a current circulating in it in such a direction that its mechanical action will tend to oppose its motion. It is necessary, however, to be perfectly sure of the direction in which the current circulates around a north and south pole, and in which direction the lines of force are flowing in a magnet.

It may be well to give a few practical examples of the various means employed for producing an induced electromotive force, such as the *magneto-electric generator* and the *induction-coil*.

THE MAGNETO-ELECTRIC GENERATOR.

68. Example of Magneto-Electric Induction.—A magneto-electric generator is a good example of magneto-electric induction. It usually consists of a permanent magnet with two coils revolving in front of its poles. Fig. 42 represents a

magneto-electric generator, in which M is a permanent horse-shoe magnet, and a, b the spools of an electromagnet fastened to the shaft g and constituting what is called an armature. By means of a crank C and the intermediate gears and pulleys G, g, P, and p, the armature is set in rapid rotation in close proximity to the magnet. The cores h, h are therefore rapidly filled with magnetic flux coming from different directions, with the result that small currents of a high electromotive force will be set flowing in the coils a, b; the latter have their ends connected to the rings c, d revolving with the shaft. These rings are insulated from each other and from the shaft, but are in electric connection with springs e and f and will thus be able to send the current to the terminals i, k.

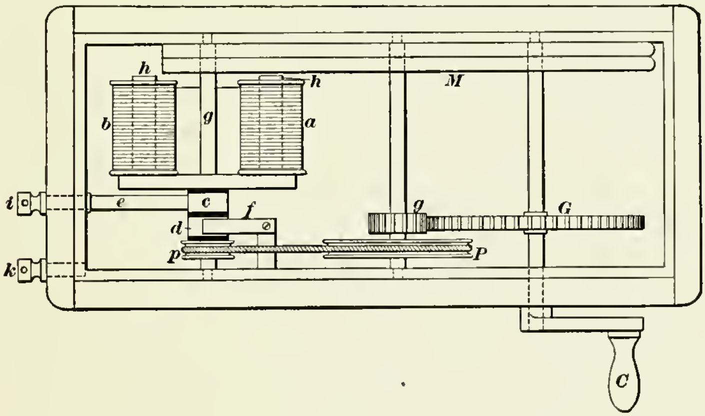

Fig. 42.

Fig. 43 gives more detailed information about the direction of the induced E. M. F. To understand how, in this instance, the lines of force cut the coils of wire, we have to imagine the magnetism at first to flow through the air from the north pole to the south pole of the magnet, while the armature is in the position indicated at (d). When moving into position (e), the armature acts as a magnetic conductor of low resistance; the lines of force will therefore shift their position and attempt to flow through the cores a and b. In so doing the flux will pass through the coils and will be cut by the wire

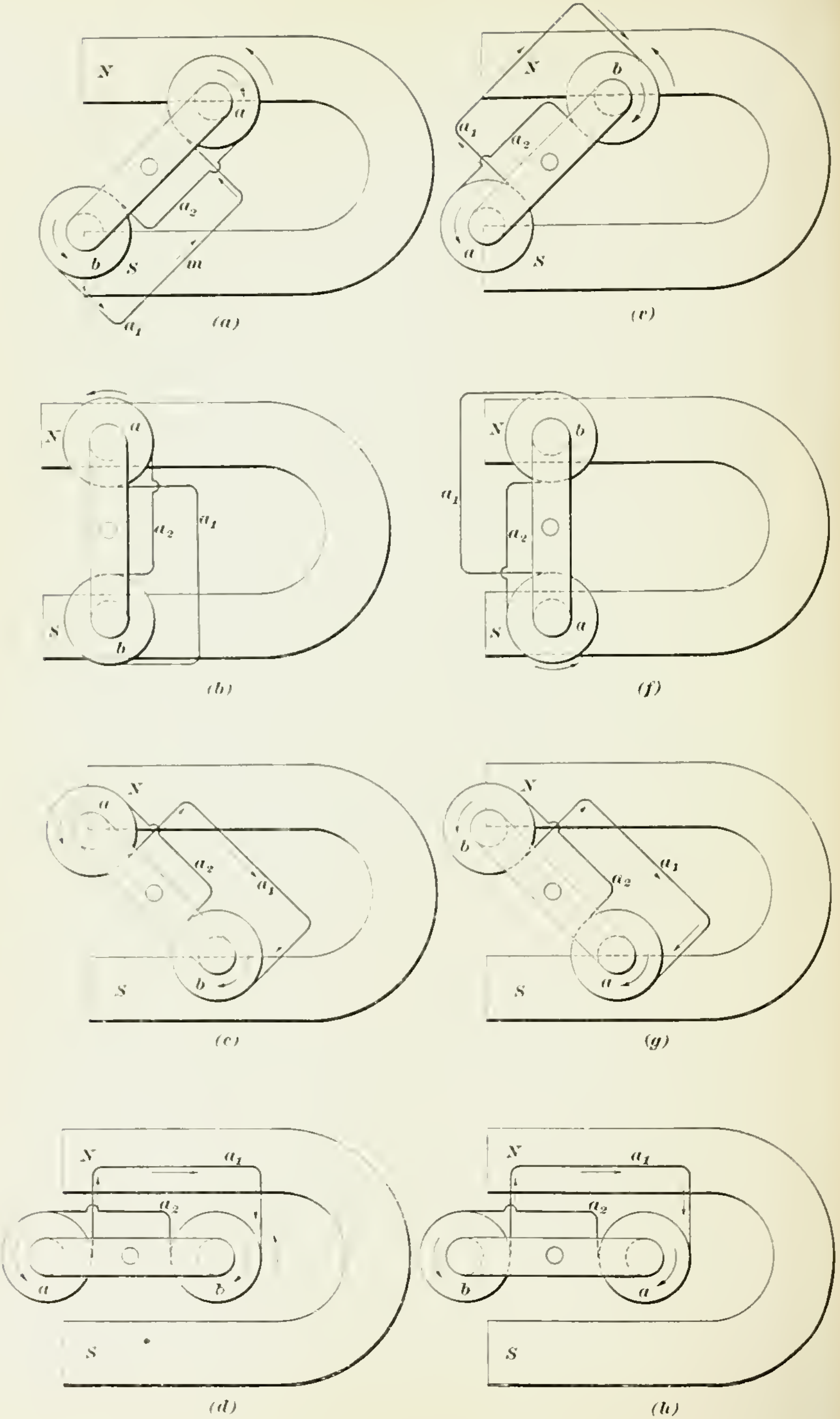

FIG. 43.

conductors in them, creating an E. M. F., the direction of which will depend on the direction of the flux. In (*a*) the coil *a* is moving toward the north pole, and magnetism will begin to flow through the cores. From previous explanations, we know that an E. M. F. will be created in the coil *a* that will tend to oppose this flow, and a current will therefore circulate in the coil in such a direction that a north pole will be created facing the magnet; the arrow on *a* indicates the direction of this current. It is unnecessary to add that the end of *a*, which is turned towards the observer, will be a south pole, and that the direction of the current in coil *b* will be contrary to that of *a*. Connecting the coils in the manner indicated, the current will flow from *b* to *a*, along the wire a_1, and return to *b* through the wire a_2. If the current should be interrupted at point *m* for any purpose, as for instance when sent through the human body, the end towards *b* would be the positive terminal, and that towards *a* the negative.

By studying Fig. 44 in conjunction with Fig. 43, it will be possible to see the magnitude and direction of the E. M. F. when the coils occupy the various positions indicated in Fig. 43. In Fig. 44 the horizontal distances between the vertical lines represent $\frac{1}{8}$ of a revolution of the armature. The vertical distances represent the E. M. F. in the coil *a*, Fig. 43. The line *XX* is the line of zero E. M. F., and points above this line represent positive E. M. F., while points below *XX* represent negative E. M. F The letters *A*, *B*, *C* indicate those points of the curve which correspond to the positions of the armature indicated by (*a*), (*b*), (*c*) in Fig. 43; thus, it will be observed that in (*a*) the coil *a* is traversed by a current of negative potential. When the armature has reached the position (*b*), the magnetic flux is at its maximum; there is neither increase nor decrease, therefore no E. M. F. and no current is present. By examining Fig. 44 we

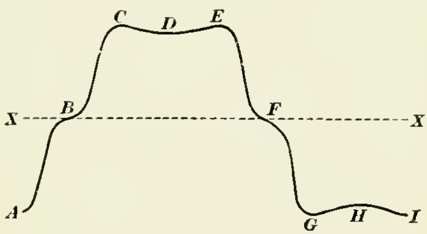

Fig. 44.

find this confirmed, and we see that in fact the current begins to change from a negative to a positive potential. When the coils have reached position (*c*) the flux has begun to decrease, and the E. M. F. is reversed and tending to maintain the magnetic flux ; the farther side of *a* will show south polarity, while the current in same has been reversed and is now of a maximum positive potential, as seen at *C*, Fig. 44. After the coil *a* leaves the position (*c*) and moves towards the position (*e*), its core is emptied of a positive and begins to fill with negative magnetic flux. The inductive effects which either of these exert on the coils are to create E. M. F. in the same direction, and the current will therefore not be reversed. In passing into position (*d*), the magnetic flux does not stop, but will be somewhat smaller by reason of the greater air-path through which it is obliged to travel. Fig. 44 shows, in fact, some decrease in E. M. F. at *D*, but shows also that at *E* it has again reached its full force. Continuing the rotation till the position *F* is reached, we have again a zero potential and a reversal of the current.

It will not be necessary to describe the behavior of the coil during the remaining part of the revolution ; the student should be able to trace it alone, and Fig. 44 will, in any case, illustrate the whole cycle. It is there noticed that the apparatus has produced an alternating current ; *B C D E F* being an alternation of a positive, and *F G H I A B* of a negative E. M. F. Comparing the curve with the positions of the armature indicated in Fig. 43, it will be seen that when *a* stands as shown in (*b*), it begins an alternation and completes it when reaching the position indicated in (*f*); then another alternation begins of an opposing E. M. F., which alternation is completed at (*b*), both together constituting a complete cycle.

69. Changing From an Alternating to a Continuous Current.—Should it be found desirable to change the current from an alternating to a direct pulsating current, then the armature must be provided with a commutator. Every dynamo is *per se* an alternator. Fig. 45 gives a diagrammatic view of an armature and commutator with the necessary

connections. The coils are marked *a* and *b* as before; their farther ends are connected with each other by means of the wire *a*, while their nearer ends are connected with the segments *c* and *d*. The segments are insulated from each other and from the shaft *g*, and the springs *e* and *f* conduct the current to the external circuit *L*. Since the current flows in the same direction while *a* travels from its lowest to its highest position, it is clear that during that period a direct current is flowing through the spring *e*. The current changes its direction when *a* has reached its highest position, but at that point the spring *e* leaves segment *c* and makes contact with *d*, which just then is provided with a current flowing in the same direction as that of segment *c* while engaged with spring *e*. The result is that a direct current is constantly flowing through the springs *e*, *f*, and the external circuit *L*; *f* being, in the present instance, the positive terminal. Fig. 46 is the curve of the E. M. F. of the armature after being rectified by the commutator.

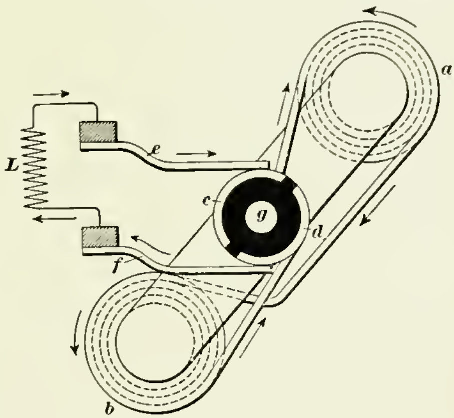

FIG. 45.

70. Faults of Magneto-Electric Generators.—A magneto-electric generator has the advantage in that it does not require a battery for its operation, but it has faults that make its use undesirable in practice; among these are the noise necessarily connected with the intermeshing of the teeth on the wheels, the labor required in operating the machine and the irritating effects of the

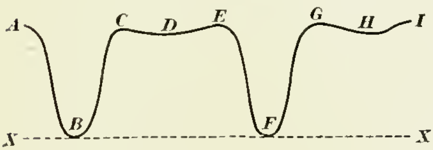

FIG. 46.

current. It is, however, a useful instrument to have on hand for emergencies, as it is always ready for work. When provided with a commutator, it has the advantage over the induction-coil in that the currents produced in the coils are of the same strength, both when the coils are approaching and when they are leaving the magnet. They are therefore physiologically equivalent, and, in addition, they have a sensible chemical effect, when rectified by means of a commutator. The ordinary magneto-electric apparatus is very little used at the present time by physicians.

THE INDUCTION-COIL.

71. Action of Induction-Coil.—Another apparatus also utilizing induction-currents for medical purposes is the *induction-coil*, which for a certain period played the leading part in electrotherapeutics.

The action of an induction-coil is based upon the phenomena of mutual and of self-induction, which were fully explained in Arts. **64** and **65**, Figs. 40 and 41. Instead of placing the coils end to end, as in the former figure, the inducing, or *primary*, coil is placed inside the secondary, and the secondary coil is moved away longitudinally only when it is desired to reduce the inductive influence of the primary coil. Since, from an electrical point of view, the primary coil is the more important of the two, it will be considered first, and, for the present, no attention will be paid to the reactive influences of the secondary coil. The therapeutic uses of the secondary coil are far more important than those of the primary coil.

Let Fig. 47 be a diagrammatic view of a solenoid with its connection to a battery and galvanometer. The solenoid P is, by means of wires g, g, attached to the galvanometer G, and, by wires e, e to the battery B. The battery-circuit contains the key K. On depressing this key, the battery will send a current through the solenoid and galvanometer in the direction indicated by the arrows, and the needle of the galvanometer will be deflected through a certain angle. We know, from former explanations, that the current does not gain its full

strength at once, because a counter E. M. F. is started in opposition to the impressed E. M. F., opposing the sudden passage of the impressed E. M. F. through the circuit. When the key is suddenly released, the circuit is open and no current passes from the battery. But the magnetic field in the solenoid is instantly closed and a strong induced E. M. F. generated, which, as we know, is in the same direction as that of the battery itself. Since it cannot pass through the battery, the current goes through the galvanometer and shows itself there to be a current of considerable strength. Although this extra current circulates through the solenoid in the same direction as did the

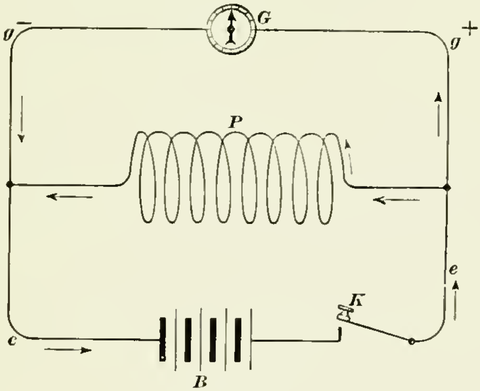

FIG. 47.

battery-current, it must pass, as can be seen by consulting the figure, through the galvanometer in a direction opposite to that of the battery-current. This is indicated by the galvanometer, as its needle now is deflected in the opposite direction. It is clear that the more sudden these interruptions and the stronger the magnetic field of the coil, the higher the E. M. F. and strength of the extra current will be.

72. Eddy-Currents.—It was said in Art. 44 that if a core of iron is inserted in a solenoid or coil it will decrease the resistance of the magnetic circuit and thus indirectly increase the number of lines of force flowing through the coil. As long as the current which is flowing does not change its direction,

it matters little whether this iron core consists of a solid rod of iron or not. But if the current is interrupted, or alternating, the case is different; then provision must be made so as to prevent the circulation of *Foucault's*, or *eddy*, currents in the core. Fig. 48 will show the position and direction of these currents. A is the coil, which is shown in a sectional view with its front half removed; in its interior is an iron tube B. If now a current is circulating around the coil in the direction of the arrow a, magnetic lines of force will be flowing through and along this coil in the directions of the arrows b_1 and b_2. Though

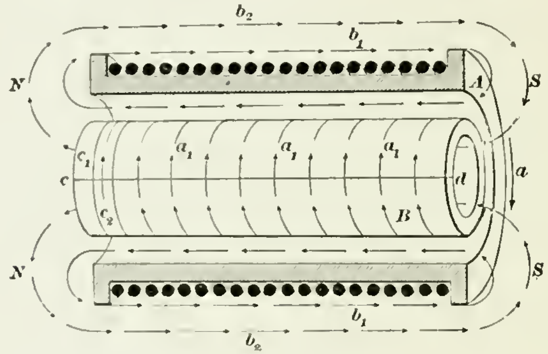

FIG. 48.

only two of these lines of force are shown to pass through the iron core, we have to suppose that this core is filled with such lines.

73. Retreating Lines of Force.—As long as the current in the coil A is flowing uniformly, no effects are produced in the core B, considering eddy-currents alone; but when the current is *reduced* in strength or *stopped* altogether, the lines of force will contract and the lines b_2 will then have to pass through the tube B and consequently produce an E. M. F. in the latter. We may suppose this tube to be made up of a great number of rings placed alongside each other, such as c_1 and c_2, or we can imagine the tube to be an endless flat conductor. In either case the *retreating* lines of force will produce an E. M. F. acting in the direction of the arrows a_1, that is, in the same direction in which the current is flowing. The

transverse area of the tube being large and the circuit short, it will offer little resistance, and a heavy current will flow in the direction of arrows a_1, wasting its energy in heating the tube. At the same time it sets up lines of force of its own, which flow in the same direction as lines b_1 and b_2 and therefore tend to maintain the existing magnetic field and prevent its decrease.

74. Again, on *starting* a current through the coil A, the lines of force b_1 and b_2 will spread out from the coil and will cut the tube B in an opposite direction. An E. M. F. will then be produced in B contrary to that of arrows a_1, and a current will be set flowing in an opposite direction to that of the current in the coil. The tube will therefore also tend to set up a magnetic field of its own, with a north pole at d, where the coil A has a south pole, as seen in the figure. Consequently, the tube tends to prevent the starting of the current in A and will delay its increase in the same manner as it previously tended to prevent its decrease or stoppage.

75. Counteracting Eddy-Currents.—We see, then, the deleterious influence of these eddy-currents and the importance of preventing their flow. As ordinarily a current is stopped by opening the circuit, we may here resort to the same means, and we could slit the tube longitudinally from c to d, and repeat those slits all along the circumference. But a simpler way would be to make up the tube of wires laid in the direction of the line $c\,d$. It should also be remembered that the iron core B, though here for sake of simplicity shown as a tube, in reality is a solid rod, and to make such a rod of wires would be a simpler matter. Sometimes these wires have a thin coat of varnish or paraffin, but they are usually left bare, relying on the resistance of their oxidized surfaces, and that of the intervening air, to prevent the circulation of eddy-currents.

76. The Primary Coil.—This function of the iron of reducing the reluctance of the magnetic circuit and of increasing the number of lines of force in the coil, has been made use of in the coil shown in Fig. 49, in which C represents such a bundle of iron wires as has just been described.

The operation of this primary coil is as follows: The battery

B sends a current through the post E and screw K to the contact D on spring F, and then through the latter to coil P. The current circulating in the coil is possessed of an E. M. F. that will produce a magnetic flux through the core C, making a magnet of the latter with a south pole at the end near the spring. In starting this current through the coil P, we meet with several obstacles which prevent the current from at once reaching its full strength. One of these is the self-induction of the coil itself, resulting from the magnetic flux around each turn which spreads through the adjoining turns and there creates E. M. F. in opposition to the impressed E. M. F. This magnetic flux does not stop here, but continues its action through

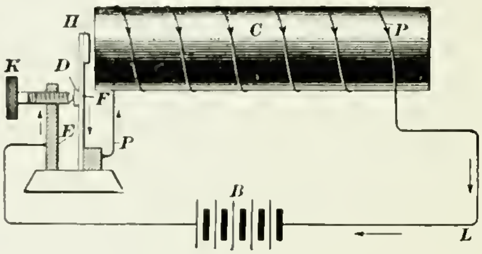

FIG. 49.

the iron core, tending to magnetize it with a north pole at H, as shown in Art. 72, having thus the effect of diminishing the magnetic flux which accompanied the starting-current. These retarding influences continue as long as the strength of the current is increasing; but they get smaller and smaller, until, when the current has reached its maximum strength, they cease altogether. At this point the magnetism of the core has increased to such a degree that it is able to overcome the tension of the spring F and attract the iron armature H. When this is taking place, the contact D, moving with the spring, leaves the screw K and the circuit is broken; hence, the lines of force return again to their original source, and in doing so they once more pass through the turns of the coil. This time they come from an opposite direction, and create an E. M. F. corresponding in direction to that of the battery-current.

Here we see the peculiar phenomenon of an E. M. F. being produced in the coil *P*, although it is cut off from the battery, and, what is more, the production of a pressure far beyond that of the impressed E. M. F. We have not far to look for an explanation of this matter, since it has already been shown that the lines of force, in closing in on the conductor, do so with great rapidity, because they are neither opposed by a counter E. M. F. nor by a counter M. M. F., and therefore the E. M. F. of the extra current has an opportunity of rising to its full height. As the induced E. M. F. depends not alone upon the density of the magnetic flux, but also upon the rapidity with which the latter moves, it can easily be seen that this extra current must be of a superior strength, since it is freed from the retarding influences which the starting-current had to overcome.

When the magnetism of the core begins to decrease after the circuit is opened, the core is unable to retain the armature *H*, and the latter returns to its initial position, once more bringing the contact *D* in touch with the screw *K*. This closes the battery-circuit again and the operation just described is repeated.

77. Breaking-Contact.—If, at breaking-contact, the coil shall develop a high E. M. F., it is evident that the interruption of the current must be accomplished with great suddenness. It has been demonstrated that the current at break is 13 times stronger than the current at make. In the apparatus just described, this was, apparently, accomplished; but there is a fault in the arrangement which has yet to be overcome. It is found that, at the moment the spring breaks contact, the resulting extra current is of an E. M. F high enough to jump across the intervening air-gap by means of a spark. This spark heats the air and therefore decreases the resistance of the gap, making it possible for a current to pass across even after the contact is broken. The result is that instead of the current being suddenly interrupted, it is gradually decreasing; hence, it is unable to produce the high E. M. F. desired. We must therefore seek means by which to prevent the sparking at contact *D*, and we find it in an arrangement wherein a *condenser* is placed in shunt across the contact-device.

78. Condenser.—A condenser has very much the same function as an air-chamber when inserted in a long pipe through which water is quickly flowing. It is well known that when the flow of water through a pipe is suddenly stopped, as, for instance, by the closing of a valve, the inertia of the water tends to maintain the flow and to bodily carry the pipe along in the same direction in which the water was flowing. That this longitudinal pull of the pipe must seriously strain its joints and connections, and that, therefore, a frequent starting and stopping of the flow must eventually cause a break somewhere in the pipe, can easily be seen.

To prevent this, long pipes are usually provided with what is called an *air-chamber*, as shown at *d*, Fig. 50. In this figure

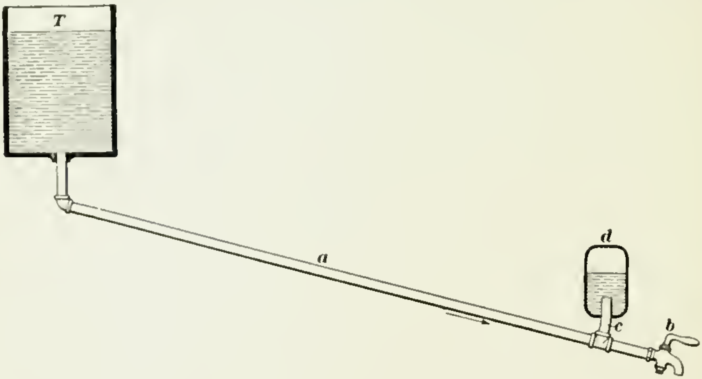

Fig. 50.

T is a tank which supplies the pipe *a* with water. If now the valve *b* is shut quickly, the water will tend to continue its motion and carry the pipe along in the direction of the arrow, and thus cause somewhat of a stress in the former. The function of the air-chamber is to prevent the sudden stoppage of the water, by giving it an opportunity of entering the chamber *d* through the pipe *c*. The air which is contained in the upper part of the chamber will then be more and more compressed by the water, thus acting somewhat like a spring, in making the water give up its energy slowly and perform a certain work of compression over a more or less extended period, instead of a sudden blow.

79. Action of a Cylinder.—In Fig. 51 the air-chamber has been replaced by a cylinder d with a piston e which is kept in a middle position by the two compression-springs f_1, f_2. The tank T communicates with the long coil a_1 by means of the pipe a, and pipes c_1, c_2 unite both ends of coil a_1 with the cylinder d. The piston e will move either to the left or right, depending on which side the pressure predominates.

Suppose now that the valve b is opened and the water set flowing through the long coil a_1, and then again the valve suddenly shut, what will be the action of piston e? The water in the coil, being prevented from passing through the valve b, will try to continue its flow through the pipe c_2; it will therefore push the piston e towards the left, and compress the spring f_1

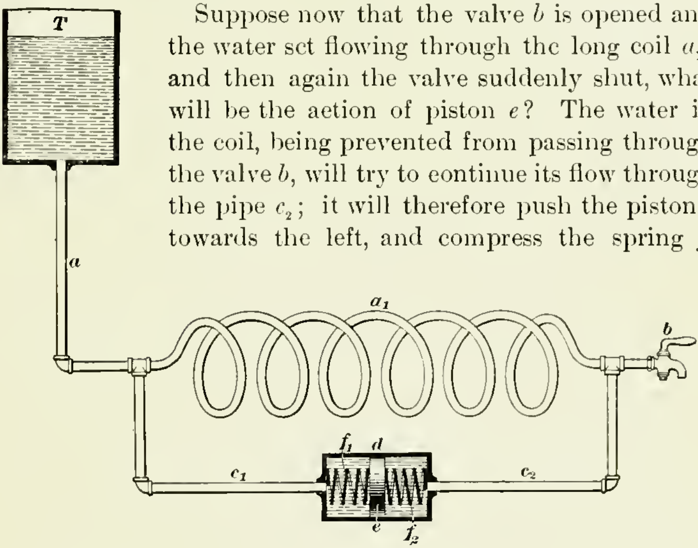

Fig. 51

until the inertia of the water is unable to compress it any further, during which operation the water has gradually come to a stop. The spring would now begin to expand again and move the piston to the right, thereby sending a current of water through the coil; but if at this moment the valve is again opened, the piston will send the water through the valve b and thus help start the flow again. In this combination the cylinder d may be said to be in parallel with the coil.

80. Cylinder in Parallel With Valve.—The arrangement shown in Fig. 52 is essentially the same, with this exception, that the cylinder is placed in parallel with the valve b. If now the current is stopped by shutting the valve b,

the water will continue to flow through the tube c_1 and force the piston e to the right until the spring f_2 is sufficiently compressed to prevent any further motion. The piston will then move to the left again, and on now opening the valve b, connection will be established between both halves of the cylinder and will enable the piston to immediately move back to its middle position, but without giving any assistance in starting the flow through the pipe a.

81. Construction of Condenser.—The action of a condenser is almost exactly the same as that of the cylinder d in Figs. 51 and 52. It will not be necessary to here enter into a detailed description of the condenser, as this will be done fully in *Electrostatics*, where "Leyden Jars" are described. It will be enough to say that a condenser may be considered as a short conductor with a very large surface, employed for storing

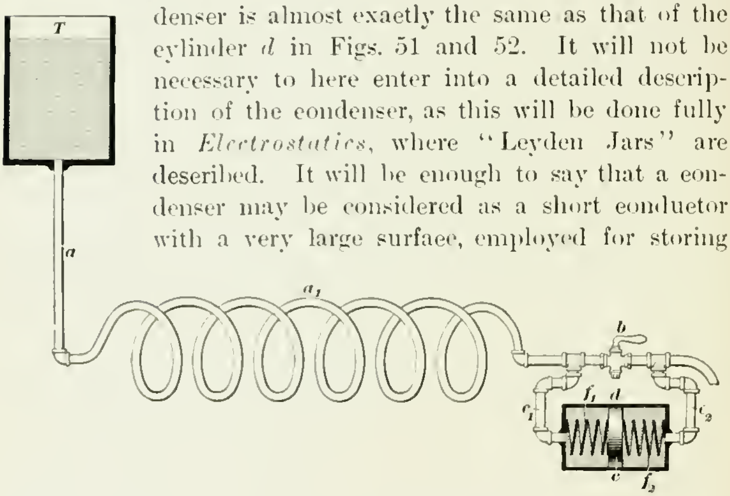

FIG. 52.

up electrostatic charges. If used for induction-coils, it consists of a number of sheets of tin-foil a and b, Fig. 53 (a), between which are inserted sheets of paraffined paper c, c. Each sheet a has a tongue of tin-foil a_1 on the left and sheets b corresponding tongues b_1 on the right side. All tongues belonging to sheets marked a are joined together and connected to a wire a_2, as shown in Fig. 53 (b), and the sheets b are similarly connected to the wire b_2. The sheets a are thus united to each other, but insulated from the sheets b. It is therefore possible, for instance, to have a positive charge on the sheets a and an equal negative charge on the sheets b, without the two charges being

able to unite, though they will have a mutual inductive influence on each other. In large coils, the amount of tin-foil used for condensers may amount to over 300 square feet.

82. Condenser and Induction-Coil Combined.—Let us now combine a condenser, as described, with an induction-coil of the form shown in Fig. 49. This has been done in Fig. 54, in which R is the condenser, connected by wires a_2 and b_2 with the coil P. The other parts are lettered in the same manner as Fig. 49, and need no additional description.

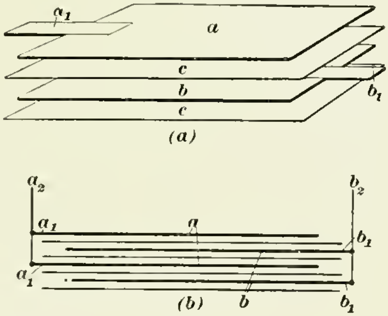

FIG. 53.

As soon as the current begins to flow through the screw K and contact D into the coil P the core will be magnetized and attract the armature H. The circuit thus being broken at D, the lines of force close in around the coil P and tend to set an

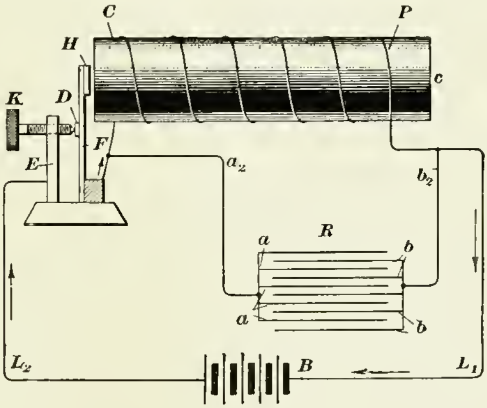

FIG. 54.

extra current flowing. In Fig. 49 the current was able, by reason of its high E. M. F., to bridge across the air-gap at D by means of a spark. In the present instance the current is

offered a path of much less resistance by going into the condenser. The result will therefore be that the current, as if possessing inertia, will continue its motion and flow through conductor b_2 into the condenser, charging the leaves b positively at the same time as the conductor a_2 will cause the leaves a to be negatively charged, and, if the capacity of the condenser is ample, the current will cease abruptly. When the spring returns to its initial position the condenser will discharge itself in the same manner as the cylinder d in Fig. 51, and will therefore send a current through conductor L_1, the battery, and L_2 into the contact D, thus aiding to start the current flowing again. The current from the condenser will by preference take the path through the battery, as the self-induction and resistance of the coil is greater.

83. Condenser in Parallel With Vibrating Spring. In Fig. 55 we have a parallel case to that of Fig. 52, as here the condenser is placed in parallel with the vibrating spring F.

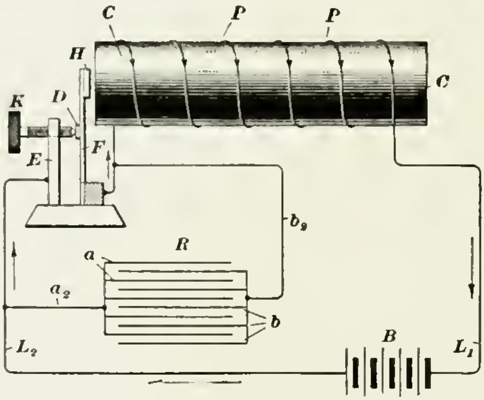

FIG. 55.

When, now, the circuit is broken the extra current will flow through L_1, the battery, and L_2 into the condenser, the leaves a being positively and b negatively charged. On again establishing contact at D, the condenser will discharge itself through conductor a_2, L_2, K, F, and b_2, and thus give no aid in starting the current through the battery.

84. Curve of Self-Induction.—It is apparent that the self-induction of the primary coil plays quite an important part in varying the E. M. F. of the primary current, by reducing it when the current begins to flow and augmenting it when interrupted. Fig. 56 (*a*) may represent the induced E. M. F. in a primary coil, when *XX* is the zero-line, and the curves above and below the line represent, respectively, positive and negative potentials. The curved line *LMNO* shows that the counter E. M. F. of self-induction is at its maximum strength at the moment when the circuit is closed, that is, at *LM*, and that it gradually decreases while the current is gaining strength, and the spreading lines of force are reaching their final positions, until it reaches *NO*, where it suddenly goes to zero. The

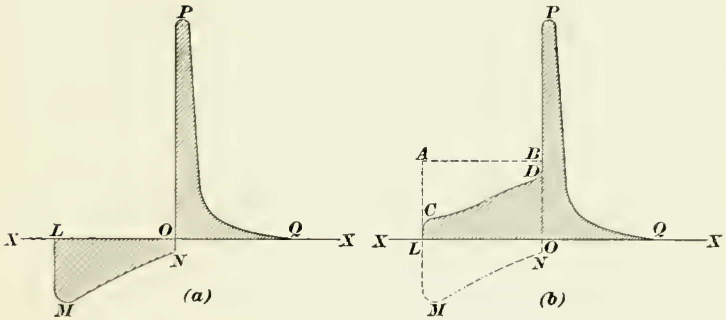

FIG. 56.

current is interrupted at this point, and the E. M. F. of self-induction instantly rises to a high positive potential at *OP*, caused by the sudden collapse of the lines of force, whence it falls back just as suddenly as it rose, and finally dies away at *Q*. To illustrate the difference between these electromotive forces, we may consider the counter E. M. F. at *LM* to be 1 volt and during $\frac{1}{100}$ part of a second to be falling to zero, while *PO* may be 6 volts and be reduced to zero in the $\frac{1}{1000}$ part of a second. It should be understood that this curve does *not* represent the *current* in the primary coil, but the E. M. F. of self-induction, which may or may not assist the impressed E. M. F., as will be shown more fully further on.

85. The Secondary Coil.—So far we have only considered the primary coil in combination with an iron core. We will now go a step further and place a secondary coil outside the primary and investigate how this secondary coil is affected inductively by the primary coil and its core.

In Fig. 57, *S* represents a secondary coil wound on the outside of the primary coil *P*; both coils are supported by a spool *O* of insulating material surrounding the iron core *C* in its

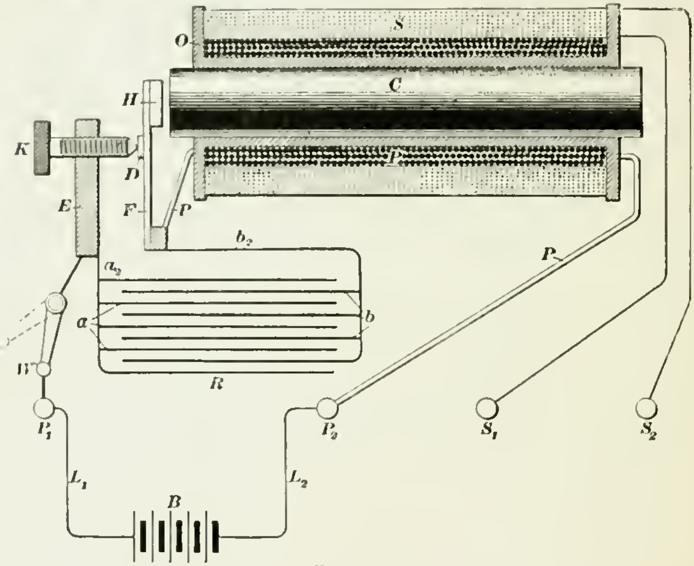

FIG. 57.

interior. A switch *W* connects the post *E* with the terminal P_1, and the terminals P_1 and P_2 are joined to the battery *B* by means of wires L_1 and L_2. The terminals S_1 and S_2 of the secondary coil are not for the present connected with each other; the secondary coil is therefore open.

86. Function of Secondary Coil.—Under these conditions the secondary coil may be considered simply as an addition to the primary coil, without being directly connected with it; that is to say, it is subjected to the *induction* of the make-current, but does not itself conduct any current. When, therefore, a current begins to flow in the primary coil and the

magnetic flux begins to spread, an E. M. F., similar to that shown by the curve $L\ M\ N\ O$ in Fig. 56 (a) is created in the secondary coil; but with this great difference, that while the E. M. F. in the one instance is in opposition to that of the primary current, and therefore powerless to do more than diminish it, in the present case it has no opposition, and is therefore able to utilize its full pressure in sending a current through the secondary coil, if its circuit is closed. It is well to emphasize this difference still more by saying that, while the make-current is flowing, there exists in the primary coil an increasing *positive* E. M. F., and in the secondary coil an increasing *negative* E. M. F. This relation between the E. M. F. continues until the current is interrupted at the point $O\ P$, Fig. 56 (a). Then the conditions in both coils are the same, because neither of them is connected with the primary battery. The closing in of the magnetic flux has, therefore, the *same* effect on both coils, that is, it creates in each a positive E. M. F. of the form shown at $O\ P\ Q$, Fig. 56 (a). In the primary coil, this means a *continuation* of the impressed E. M. F., but of a greater magnitude, while in the secondary coil it means an E. M. F. in opposite direction to that in the latter existing E. M. F. We may conclude from this that, with an open secondary circuit, both coils are subjected to the same inductive influences, but with different results, so that, while the E. M. F. in the primary coil is of a direct and intermittent nature, in the secondary coil it is alternating. In both cases the waves are dissymmetrical, because the waves produced at breaking-contact are of a greater magnitude.

87. E. M. F. of Secondary and Primary Coil.—If, as is supposed, the coils are subjected to the same inductive influences, the induced E. M. F. should be the same, provided that both coils contain the same number of turns. Ordinarily the secondary coil consists of many more turns than the primary, and the same magnetic flux would therefore produce a higher E. M. F. in the secondary coil, the increase being directly proportional to the added number of turns. It is easy to see why this must be so. Take, for instance, a piece of wire

4 inches long, and let 100 lines of force move across it, producing a certain E. M. F. in the wire. If now a wire 400 inches long is so arranged or wound that the space it occupies is not more than 4 inches in length, the whole wire will be simultaneously cut by the 100 lines of force; that is, every 4 inches of the wire will have the same E. M. F. produced in it as the original short piece. The long wire will therefore have an E. M. F. 100 times larger than the small wire. Thus the primary coil may, for instance, consist of 80 turns, while the secondary may contain 4,000 turns; hence, the E. M. F. in the secondary coil should be 50 times as great as that in the primary. Fig. 56 (*a*) might represent these electromotive forces in the secondary coil if the vertical lines *L M*, *N O*, and *O P* were made 50 times as long, and the curved parts connecting them drawn parallel to *M N* and *P Q*. If *L M* and *O P*, respectively, represent 1 and 6 volts, then the corresponding values for the longer secondary coil would be, respectively, 50 and 300 volts.

88. Effect of Secondary on Primary Coil.—So far the secondary coil has had no effect on the primary coil, because no current has passed through the former; but let the terminals S_1 and S_2, Fig. 57, be connected to some external circuit, then the conditions will be materially altered. The high E. M. F. generated in the secondary coil has now an opportunity of starting a current; but in doing so, it will immediately create a M. M. F. which will not alone send a magnetic flux through the secondary, but also through the primary coil. It will set up a counter E. M. F. in the secondary in opposition to that of the secondary current, while, in the iron core, it will set up a magnetic flux in opposition to that produced by the primary current.

That the current in the secondary coil should have this obstructing effect on the flow of the primary current ought not to come entirely unexpected, as it must derive its E. M. F. from some source. It is therefore evident that the energy displayed in the secondary coil is taken from the primary current after contact is made. The extent of these reactions, due to the secondary coil, depends upon the strength of the current flowing

in the latter, which is again controlled by the resistance of the coil and the external circuit, and by the self-induction of the coil.

89. Reduction of Voltage in Secondary.—We saw above that the E. M. F. in the secondary coil at breaking might be 300 volts, when no current was flowing; but this voltage suffers a very great reduction when a current is permitted to circulate. On the insertion of a comparatively low resistance, the potential difference at the secondary terminals may be only two or three volts. Even with a resistance of 1,000 ohms, the E. M. F. would be very low, ordinarily from 10 to 15 volts, as long as we deal with small coils; with large coils these values are of course much greater. This is caused partly by the reaction of the secondary current on the primary circuit, but principally by the self-induction in the secondary circuit itself. At the time when the induced E. M. F. is at its maximum, and when a heavy current *might* flow, it is most effectually stopped by the powerful choking action of the coil, which does not permit a sudden rise or a sudden fall of pressure. In addition to these inductive reactions, the E. M. F. will also suffer a great reduction by the resistance of the very long, thin wire of the secondary coil. The secondary current, therefore, after it has been subjected to all these influences, emerges not only in a very much enfeebled condition, but the character of its waves has also undergone a great change; the rough edges have, so to speak, been cut away.

90. In their present form they may appear as the waves shown in Fig. 58, in which the changes are seen to be less

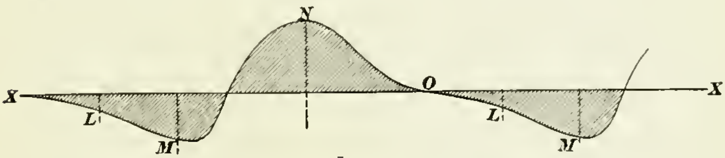

Fig. 58.

abrupt. Here we observe that, when the spring makes contact at point N, the pressure begins to increase gradually, but is not permitted to reach its maximum value before the contact at M

is broken. The E. M. F. is now suddenly reversed and rises to its full value at N, whence it slowly descends until point O is again reached, contact made, and the cycle repeated. A secondary coil made of long, thin wire, by reason of its high self-induction, has a soothing effect, but even then we may see that the wave is always steeper on breaking contact; *in fact, it is impossible to make the waves of the induced E. M. F. of a symmetrical form.* Should it be desirable to have the waves act more abruptly, the number of turns in the secondary circuit should be reduced, thereby reducing its self-induction and resistance. In addition to this, the number of interruptions per second should be lessened, giving the current time to reach its full strength.

91. E. M. F. Curve of the Battery-Current.—As Figs. 56 (a) and 58 give the curves of the induced E. M. F only, it may be well also to show the E. M. F. curve of the battery-current after it has been affected by the counter E. M. F. of self-induction in the primary coil. Let the line $A\,B$ in Fig. 56 (b) represent the available E. M. F. of the battery, and the dotted line $L\,M\,N\,O$ the counter E. M. F. arising on making contact. If the primary coil had been devoid of this self-induction, the line $A\,B$ would show the E. M. F of the primary coil; but as the E. M. F. is acting in opposition, the latter must be deducted from the former, and the E. M. F. of $L\,C\,D$ remains, which, in addition to the curve $D\,P\,Q$ of the extra current, gives the whole active E. M. F. of the primary coil, if the secondary circuit is open. On closing the latter, the primary E. M. F is affected more or less, depending on the inductive influence of the secondary coil.

92. Use of the Primary Current in Medicine.—The primary current is employed in medical treatment when the resistance is low and a larger volume of current than the secondary coil can furnish is required. To show how a resistance affects these dissimilar coils, let us suppose that the E. M. F. of the primary coil is 5 volts and its resistance 1 ohm, while the E. M. F. of the secondary coil is 100 volts and resistance 1,000 ohms. If the currents of these coils are sent through a

galvanometer of 4 ohms resistance, we have, according to Ohm's law, in the first coil a current of : $\frac{E}{R} = \frac{5}{1+4} = 1$ ampere ; and in the secondary coil, $\frac{100}{1,000+4} = .0996$ ampere. On increasing the resistance of the galvanometer to 50 ohms, the current in the primary coil is $\frac{5}{1+50} = .098$ ampere, and in the secondary coil, $\frac{100}{1,000+50} = .0952$ ampere, that is, the currents in the two coils are very nearly the same. But let the resistance be increased to that of the human body, or about 2,000 ohms, then the difference will be most marked. In the primary coil the current will now be $\frac{5}{1+2,000} = .0025$ ampere, while that in the secondary is, $\frac{100}{2,000+1,000} = .033$ ampere. In the latter instance the current in the secondary coil is more than 13 times the strength of that in the primary coil. It is therefore clear that, in order to apply percutaneously the "extra current" of the primary coil, the electrodes must be large and the skin well moistened to diminish external resistance.

In speaking of voltage and strength of this induced current, it is well to call attention to some points that are often misunderstood. It has, for instance, been claimed that a smaller quantity of electricity comes out of the primary coil than goes into it. We know from previous explanations that this is impossible ; that, in fact, whatever quantity of electricity enters the coil will leave it again undiminished. This idea very likely has been based on the well-known fact that the current that enters the primary coil is smaller than it ought to be, if it simply depended on the resistance of the coil and the available E. M. F. of the battery. But it was shown in Art. 84 that the reason for this reduced strength was to be found in the self-induction of the primary coil.

93. Effects of a Dissymmetrical Alternating Current.—The E. M. F. in Fig. 58 is alternating ; but notwithstanding this, its physiological effects may be that of an

unidirectional current. The "break-current" is thirteen times stronger than the "make-current." This break-current is the only one that acts on the tissues or organs; the dissymmetrical alternating current may, therefore, be said to be unidirectional. To understand this better, let us use as an illustration an air-pump, as shown in Fig. 59, in which *A* is a cylinder and *B* a piston moving from one end of the cylinder to the other.

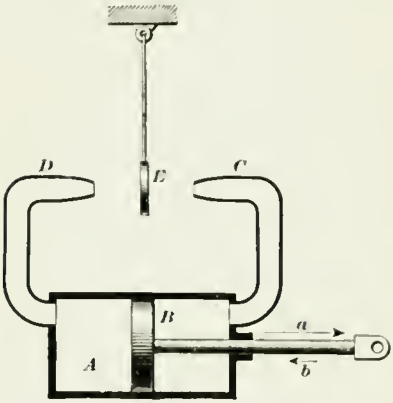

Fig. 59.

D and *C* are pipes connected with the ends of the cylinder, and *E* a vane suspended in the manner of a pendulum. If, now, the piston should begin a reciprocating motion with the same speed in both directions, it would produce effects similar to those of an alternating E. M. F. The air would escape alternately from the pipes *C* and *D* and blow against the vane, causing the latter to oscillate from side to side. This would correspond to the action of symmetrical alternating currents, when the effect of either terminal would be the same.

But suppose the piston to move with speeds corresponding to those indicated by the lengths of the arrows *a* and *b*. We may then imagine the piston speed towards the left to be so slow that the current of air escaping from *D* could barely be perceived, and that its influence on the vane would be negligible, while the air passing from *C* would be ejected with a high speed, forcing the vane strongly to the left. Considering the vane simply as a pressure-indicator, we would come to the conclusion that the air-pump produces a pressure on only one side of the piston, and that of an intermittent nature. Let the vane be now removed and a rubber tube slipped over the pipes *C* and *D*, transforming the whole into one continuous pipe in which, at some convenient point, a current-meter has been inserted. When the piston begins its uneven motion, the

meter makes no distinction between the pressure on one side or the other. It merely indicates that so many cubic feet of air pass at each stroke of the piston, irrespective of its pressure. Judging from these indications, we should say an alternating current was passing and that the effects were the same in either direction.

94. Effects of Induction-Currents.—The same conditions determine the effects of the induction-current on the human body. It requires a certain pressure of the current to excite the muscles; to a pressure below this the muscles do not respond. When, therefore, an alternating current is flowing from a secondary coil, the effect on the muscles will be the same as that of the air-current on the vane. Though the current in *reality* is alternately flowing in both directions, *physiologically* it is unidirectional, and it will therefore make a difference which of the electrodes is placed on the muscle. On the other hand, when it comes to those effects where it is simply a question of current-volume, it is immaterial how the coil is connected with the body, as the same volume of electricity passes through either electrode. The case is then similar to the air-pump with both pipes connected by the rubber tube.

95. Effects of Changing the Number of Turns in Secondary Coil.—It must be remembered that by changing the number of turns in the secondary coil, the voltage and amperage will be changed according to certain fixed laws. For instance, by increasing the diameter of the wire and reducing the number of turns, the induced E. M. F. is necessarily reduced, while the amperage is increased. Other conditions remaining the same, the product of the two should be a constant. Therefore, a reduction of the wire diameter with an increased number of turns should necessarily be followed by a reduced amperage and an increased E. M. F. That this product is *not* a constant is caused by the self-induction of the coil; but, nevertheless, the tendency is in that direction, and when it is claimed, as it has been, that the length of the coil is immaterial, it is well to remember these facts as a general guide to the right use of the coil.

96. Variation of Electromotive Force in an Induction-Coil.—For therapeutic uses, it is important that the active part of the secondary coil is variable, so as to create a high or a low E. M. F. and to vary the strength of the current. It is also of advantage to be able to use the primary coil alone, or in conjunction with the secondary coil, as a curative agent. Fig. 60 shows the primary coil connected in such a manner that its induced extra current may be sent through the human body. P' and P'' are, as before, the terminals of the primary coil, while P''' is connected with the vibrating spring and also with one end of the primary coil. If, now, P'' and P''' are provided with conducting-cords and electrodes and the latter held in the

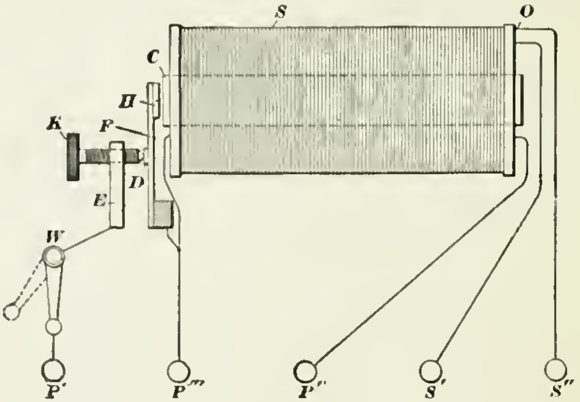

FIG. 60.

hands, a distinct shock will be felt when the spring breaks contact, because the human body is the only path left open by which the current may pass. On making contact no sensation will be felt, since in that case the voltage is very low, in fact, below the E. M. F. of the cells, as previously shown in Fig. 56 (*b*).

97. Another combination, in which the primary coil may be used singly or in conjunction with the secondary coil, is that shown in Fig. 61. Here the end p_2 of the primary coil and the beginning s_1 of the secondary coil, are joined to the spring of the contact-device *F*. The beginning p_1 of the primary coil is connected to the switch *W* and the latter eventually to the

terminal P_2. The end s_2 of the secondary coil is connected to the terminal S_2. Between the terminals P_2 and S_1 we have now the E. M. F. of the primary coil, and between S_1 and S_2 the E. M. F. of the secondary coil alone. Finally, between the terminals P_2 and S_2 we have the combined E. M. F. of both coils. The contact-device F connects the end of p_2 of the primary coil with the beginning s_1 of the secondary coil, making one coil of both. It will therefore be necessary to use P_2,

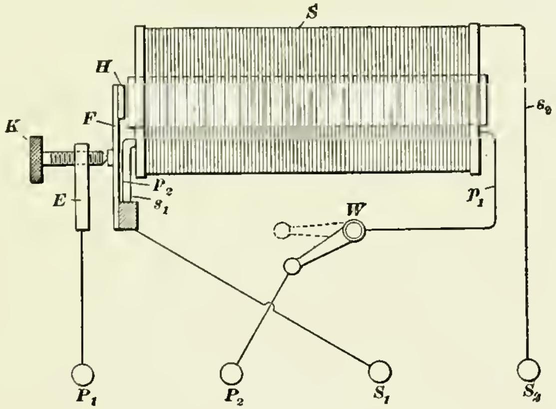

FIG. 61.

which connects with the beginning p_1 of the primary coil, and the terminal s_2 of the secondary coil, to have both coils connected as one.

98. E. M. F. Generated by the Secondary Coil.—It has been shown that the E. M. F. generated by the secondary coil depends upon the strength of the magnetic field and on the number of turns in the coil; likewise on the speed with which the magnetic flux fills and empties these turns, and on the number of interruptions per second. The strength of the magnetic field in the first place depends on the number of cells connected with the primary coil and the number of turns in the latter. With the primary coil and the magnetic flux in same considered as a constant, the E. M. F. of the secondary coil may be altered, either by changing the effect of the magnetic flux on it, or by altering the speed of the vibrator.

99. Dubois-Raymond Regulator.—The first of these methods—that is, varying the effect of the magnetic flux on the secondary coil—may be carried out in various ways. We will consider briefly the most important of these, as recent practise tends to abandon them all with one exception, the aim being to avoid complicated devices, when better and surer results may be reached by instruments constructed on more scientific principles.

One of the earlier forms of regulators for this purpose was of the so-called *Dubois-Raymond* type. In this the primary coil with its iron core was stationary, while the secondary coil was separate and could be moved away from the primary, enclosing it more or less according to the E. M. F. it was desired to develop in the secondary coil. It can easily be seen that a withdrawal of the secondary coil from the inductive influence of the primary coil must weaken the resulting E. M. F. in the former, because part of the secondary coil is entirely out of reach of the lines of force, and therefore inactive so far as producing an E. M. F is concerned, but still influencing the current by means of the self-induction and resistance of the whole coil. The base of the coil is provided ordinarily with a millimeter scale which enables the operator to read off in millimeters the distance between the coils. It is claimed that by the use of this millimeter scale one can at any time reestablish with sufficient accuracy for clinical purposes the conditions which existed during former treatments. This is the only advantage of the scale, for as an indicator of current-strength it is without value, and must not be considered as such. An instrument of this class is often provided with several secondary coils, making it possible to substitute one of finer wire for others of coarser wire, while at the same time the primary coil remains stationary and unaltered.

Instead of having several loose secondary coils, there may be two or three such coils fastened permanently to the base, either of the coils being thrown into action by means of a switch, and each of them operated by its own vibrator, or by a vibrator which is common for all. This is the form of secondary coil now generally used.

100. Screening Effects.—It is not absolutely necessary to move the secondary coil out of the magnetic field in order to diminish its action; it may remain in its original position and the force of the magnetic waves be diminished before they reach the coil. We have already seen that the iron core had to be subdivided to prevent the formation of eddy-currents. The existence of these currents in conductors of large diameters has a screening effect on coils situated either inside or outside of said conductor, and may therefore be used as a means for weakening the action of the magnetic field. Ordinarily, a space is left open between the iron core and the spool, large enough to allow the insertion of a metal tube. If the tube is pushed in far enough to cover the whole length of the core, it reacts so strongly on the primary current that only a very feeble E. M. F. is generated in the secondary coil. To understand this, it must be borne in mind that the tube practically constitutes a secondary coil. It is true that, strictly speaking, it consists of one turn only; but this one turn is of a large cross-sectional area, and only a few inches in length, and consequently of very low resistance. When, therefore, the magnetic flux passes and repasses through the shield, it produces, although the E. M. F. is small, rather powerful secondary currents and a M. M. F. in a contrary direction to that of the primary coil. It therefore counteracts the effects of the primary circuit, and the result is that only a feeble magnetic flux reaches the secondary coil. A gradual withdrawal of the tube of course dimishes its reactive influence and permits the E. M. F. in the secondary coil to increase. This tube need not necessarily be placed around the core; it may be situated between the primary and secondary coil, or over the secondary coil alone. In either case the action of the tube is the same. In a scientific faradic apparatus the shield is not used.

101. Modern Methods of Regulation.—Neither of these methods of regulation is much used in modern induction-coils. The aim has been rather to avoid all loose and movable parts, as being a source of confusion and uncertainty, and to place all the coils in a fixed position. When the various coils

are to be thrown in and out of action, it is effected by the aid of switches to which the terminals of the coils have to be connected. The positions of the coils may be such that they are either placed inside of one another or side by side.

An example of the first arrangement is shown in Fig. 62. The terminals of the battery B are attached to P_1 and P_2, which in turn connect with the pole-reverser V. The current flows from V through the wire w_2 to the contact-spring F and the post F_1, and thence through wire p to the primary coil P, from which it returns to the reverser through the wire w_1. The secondary coil S_1, made of very fine wire, has one of its ends

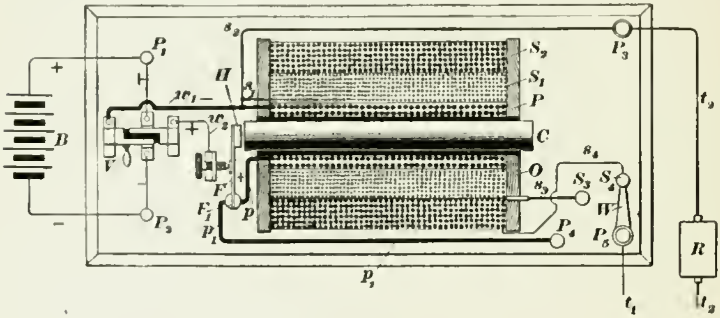

FIG. 62.

joined to the wires w_1 and s_2; the latter is connected with the terminal P_3. The other end of S_1 and the beginning of the coil S_2 are both attached to the wire s_3 that is connected to the contact S_3. The end of the coil S_2 is by means of the wire s_4 united with the contact S_4; and finally the post F_1 is connected to the contact P_4 through the wire p_1. The terminal of the switch W is P_5, which, together with the terminal P_3, constitute the terminals of the induction-coil, to which the conductors t_1 and t_2 are attached.

In the present instance, the secondary coil has only two subdivisions; but in all modern faradic batteries there are six, made up of three different sizes of wire. The switch with its connections will not be affected by this increased number, and the arrangement shown in the figure will in the main be retained. The operation of the coil is the same as before; the new features

are to be found in the pole-reverser V and the switch W. The former will be described later on; it will suffice at this point to say that, by moving the handle to the other side, the wire w_2 becomes negative, instead of wire w_1, as at present. When the switch W is connected with the contact P_4, the primary current alone is received through the conductors t_1 and t_2. Turning the switch to the contact S_3, the alternating current of the secondary coil S_1 is sent through the terminals; and finally, when the switch reaches the position indicated in the figure, the united E. M. F. of both the coil S_1 and the coil S_2 will be received.

The current may be regulated by means of the rheostat R in the primary or secondary circuit to any desired strength, and any sudden fluctuations may thus be avoided when changing from one coil to another. The switch need not necessarily be placed on the base of the induction-coil; it is frequently placed on one end of the spool.

102. Compound Secondary Coils.—Experience proves that a limited number of secondary coils do not serve the purposes for which they are intended in electrotherapeutics, and that certain effects aimed for, notably those of a sedative influence, are altogether impossible. Various combinations of coils have been suggested as fulfilling all requirements, and as these agree pretty closely, it is necessary to give but one of them. Hence, the following arrangement suggested by one of the leading practitioners in that line, will suffice:

The primary coil,	made of No. 21 wire,	84 yd. long.
First secondary coil,	made of No. 21 wire,	100 yd. long.
Second secondary coil,	made of No. 21 wire,	150 yd. long.
Third secondary coil,	made of No. 32 wire,	300 yd. long.
Fourth secondary coil,	made of No. 32 wire,	500 yd. long.
Fifth secondary coil,	made of No. 36 wire,	500 yd. long.
Sixth secondary coil,	made of No. 36 wire,	1,000 yd. long.

Adding, total length of secondary coil equals 2,550 yd.

The end of each coil is joined to the beginning of the adjoining coil and each junction connected with a contact-button.

103. Methods of Effecting Combinations.—There are various means for effecting the desired combinations of the secondary coils, or the primary and the secondary coils. A device of this kind, with its connections, is shown in the diagram in Fig. 63. The studs Z are supposed to be arranged

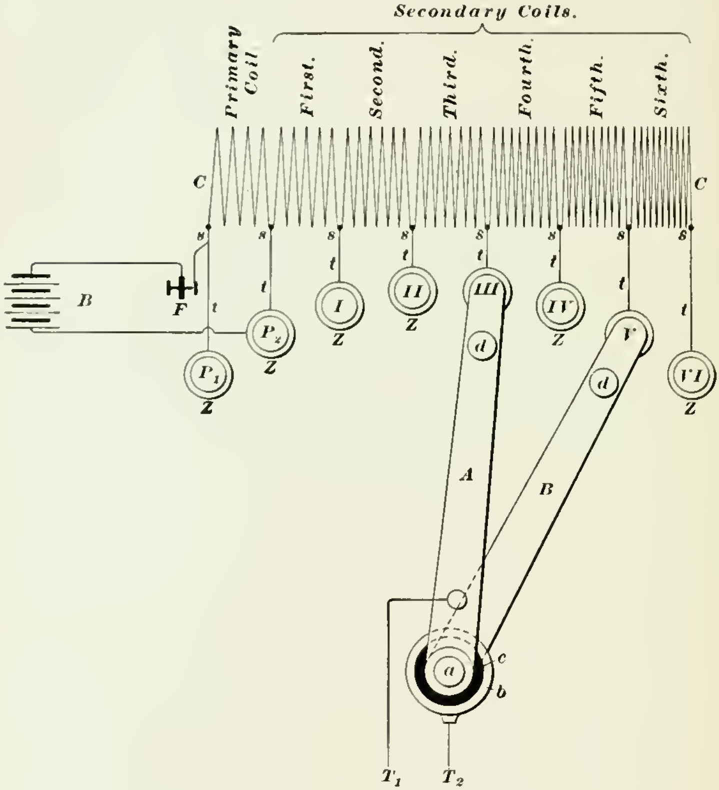

FIG. 63.

on a plate of insulating material in any convenient place near the induction-coil, and the arms A, B are supported by the plate in such a manner that they can be moved from stud to stud by means of the small knobs d, d. The arm A swings on the pin a, which is surrounded by a bushing c of insulating material; it is therefore insulated from the ring b to which the

other arm B is attached. The conductors T_1 and T_2 leading to the electrodes are connected in any suitable manner to A and B, respectively. In this instance they are shown, for the sake of clearness, fastened directly to the arms. The primary battery B is connected to the vibrator F and the stud P_2, while the stud P_1 is joined to the primary coil near F.

All the coils are connected with one another so as to make one continuous coil, and the junctions of the coils are again joined to the studs by means of the conductors t. One end of the last is, as one end of the first coil, likewise joined to a stud, as shown in the figure. The coils are in reality supposed to be wound so as to surround each other, as in Fig. 62, and not side by side, as indicated in this figure. It can easily be seen that by thus insulating the arms A, B from each other it is possible to select any separate coil and to use its current alone or to add any other coil that may be necessary for the proper voltage or strength. By placing the arm A on P_1, and B on P_2, the primary coil alone may be utilized, or the first secondary coil may be added by moving B to stud I. Any further motion of B towards the right adds a coil for each stud it passes, until, when it reaches stud VI, the whole coil is included in the circuit. In the position of the arms shown in the diagram, only the fourth and fifth secondary coils are in the circuit. By moving arm A to IV the fifth coil alone would be in use.

It has already been shown in Arts. **115-122**, *Direct Currents*, how the cells that operate an induction-coil may be combined to give the desired voltage.

104. The Speed of the Vibrator.—Having considered the first method of varying the E. M. F. in the secondary coil, we will now proceed to the second, that of varying the speed of the vibrator.

The contact-spring, shown in Figs. 49 and 62, does not admit of much variation in regard to frequency. The usual method is to advance the screw K towards the spring, thereby bending the spring out of its original position, and causing it to exert a heavier pressure against the platinum contact D. The distance through which it moves is now shorter and its motion quicker,

resulting in an increased number of vibrations per second. The increase in frequency obtainable in this manner is not very great, and it is seldom that the original speed can be doubled. It may be improved somewhat by adding another screw K_1 near the base, as shown in Fig. 64, thereby shortening the active part of the spring. The frequency of a good spring-vibrator varies from 150 to 300 interruptions per second.

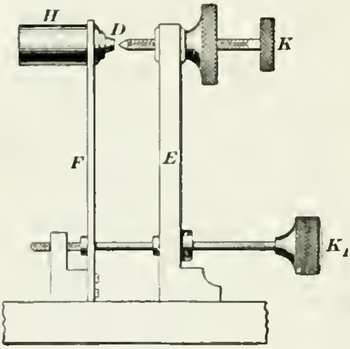

FIG. 64.

105. Ribbon Vibrator. If it is desired to increase the frequency still further, a *ribbon vibrator*, such as is illustrated in Fig. 65, may be used. The steel ribbon *r* is fastened to a post *a* and supported by another post *b* through which the ribbon passes. The contact-screw *c* regulates the pressure and the rate of vibration. An additional means for regulation is found in the lever *e* to which one end of the ribbon is connected. The screw *d* engages this lever and can, by forcing it away from the

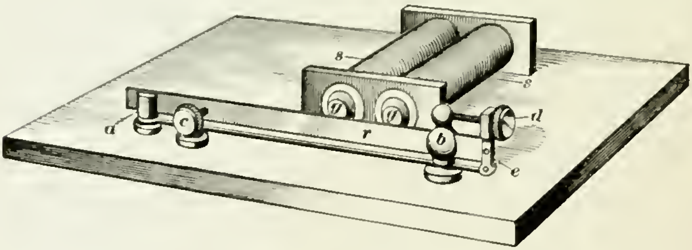

FIG. 65.

post *b*, subject the ribbon to an increased tension, followed by a still higher rate of vibration. The iron cores are shown at *g*, *g*, and *s*. *s* are the secondary coils, one of which is made of rather coarse wire. The ribbon vibrator is connected with the fine-wire coil, and gives an alternating current of rather high frequency, in which the waves are smooth and devoid of any abrupt changes.

The other coil is used in combination with a slow vibrator separately illustrated in Fig. 66, wherein *F* is a spring with an iron armature *H* and an extension *D* carrying a small weight *W*. The weight can be fastened in several positions to correspond with the changes in the rate of vibration. The contact-screw is shown at *K*, and *C* is a small electromagnet operated by the primary current. When placing the weight *W* at the extreme right, the vibrations are the slowest obtainable. Moving the weight towards *K* increases the rate of vibration, and if *W* be taken off altogether the make and break is very rapid. Since the coil is made of a coarse wire and with few turns, the current will necessarily be of a low E. M. F. with sudden changes.

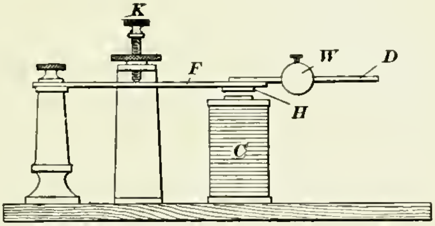

FIG. 66.

106. High-Speed Vibrator.—A vibrator that is claimed to be capable of varying the rate of the interruptions from 50 to 1,500 per minute, is illustrated in Fig. 67. The head *A* of a spool is provided with a disk *B* which is free to revolve on the pin *O*. The disk carries a spool *C*, and a pendulum *D* pivoted in the bracket *P*. The pendulum is provided with an adjustable weight *W* and an iron armature *H*. The slotted lever *E* carries, at one of its extremities, a pin *K* adapted to engage the spring *F* and push it more or less against the pendulum. The lever is pivoted on the post *L*, and its slotted end engages a stationary pin *M*. When the disk *B* is turned to the right by means of the handle *N*, the pin *K* is swung to the left, thus shortening the active part of the spring, and making it stiffer. The rate of vibration is therefore increased. On turning the disk to the left the spring is not only made weaker, but the pendulum hangs in a position more nearly vertical, and exerts a smaller pressure against the spring. When the handle *N* has finally reached its extreme position at the left, the pendulum will come to a complete stop.

107. Effect of Excessive Frequency of Vibration. It might seem, at first glance, that if a high E. M. F. were desirable, the frequency of vibration could not be made too high; but unfortunately the E. M. F increases with the frequency only up to a certain point. Beyond this, other factors appear, with a constantly increasing influence, and prevent a further rise of E. M. F. When this point is reached, the time for the full action of the primary current is cut short, and the E. M. F cannot increase. The magnetic flux being limited, it follows that the secondary current must be affected in a similar manner, and the increase that should have resulted from the high speed of the moving magnetic field is cut down by the high counter E. M. F. following in its wake. Therefore, if an increase of E. M. F. is looked for, the results are disappointing; but, on the other hand, a material gain is realized in the smooth form of the alternating current. Consequently, in the modern medical coils, the frequency of vibration is pushed as high as 10,000 to 15,000 interruptions per minute, the object in view being rather to procure a current of a peculiar soothing nature, than one of a high E. M. F. A current of this kind can be obtained only by means of a perfect vibrator, the action of which is even, and not of a jerky character. Should, for instance, a spring, while vibrating at a high speed, reduce its

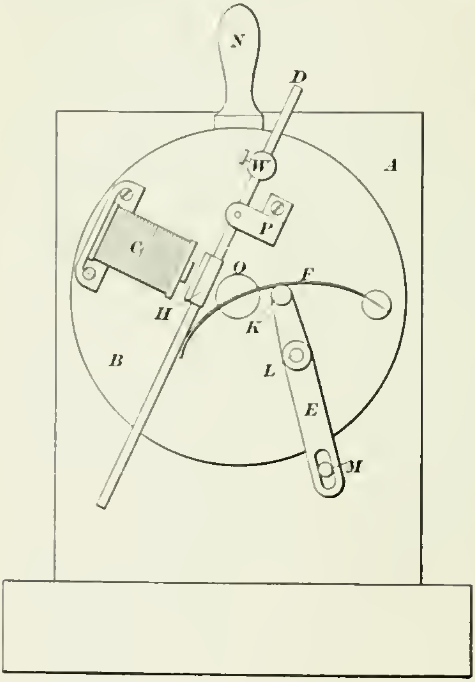

Fig. 67

speed or stop at certain intervals, then such variation would at once be accompanied by a wave of high E. M. F., which would have a decidedly unpleasant effect and spoil the work of an otherwise perfect instrument. For this reason it is important that the action of a vibrator be examined very closely in order to discover whether it is subject to such irregularities.

108. Testing an Induction-Coil.—When examining a coil, first see if its E. M. F. is high enough for the production of what is called high-tension currents. For this purpose a Geissler tube of moderate size, say three to four inches long, is very useful. The terminals of the secondary coil are connected to the Geissler tube by means of two short pieces of copper wire, and, after the room has been darkened, the coil is set in operation. Unless the secondary coil contains at least as much wire as the coil mentioned in the table in Art. **102**, that is, about 2,550 yards of Nos. 21, 32, and 36, no effect will be produced. If the voltage is sufficient, the tube will glow, and its brightness will increase with a rise in E. M. F.

After it has been proved that the coil has sufficient voltage, the Geissler tube may be employed to study more closely the action of the vibrator. The tube will show patches of light of a cup-like form, with a wavy motion. If the motion is uneven and of an intermittent nature, it is proof that the action of the spring is irregular, and that the interrupter must be adjusted until the vibrations are even. These experiments should be repeated with one or more cells until the entire strength of the battery has been employed in the test.

A more delicate and efficient test may be performed by means of an ordinary telephone receiver. It is connected to the coil by the usual conducting-cords, and when placed to the ear will indicate every variation in E. M. F. both in the primary and in the secondary coil. Irregularities in vibratory action that would otherwise pass unobserved would be quickly detected by this method.

The bipolar electrode may also be used for testing the regularity of the vibratory action of the interrupter. After the electrode has been connected to the secondary coil, the tips of

two fingers should be placed one on each side of the metal rings. When used with the coils of fine wire, a light touch of the fingers is sufficient to discover irregularities in the current; while for larger currents it is necessary to hold the electrode tightly in one hand.

MEASUREMENT OF CURRENT-STRENGTH.

109. When an ordinary galvanic current is used for therapeutic purposes we find, as was shown in previous pages, no difficulty in measuring its quantity and adjusting the latter to any desired amount. This is important with a current of its character, because its action is often so weak that one would be ignorant of its presence but for the indications of the ammeter. When it comes to the alternating current of the induction-coil, the conditions are changed. Here the ordinary ammeter will no longer serve as a measuring instrument, because the direction of the current is constantly changing, and changing so rapidly that it is impossible for the moving parts of the instrument to follow these reversals, and apparently no current is passing. Attempting to use a voltmeter and measure the pressure in place of the strength of the current, the result would be the same. The variations in pressure are so sudden that in this case also the pointer will be unable to trace them. Even should it succeed in doing so, the indications would be of no value. We should see a maximum E. M. F. of a certain value indicated during every alternation, but would be unable to determine the average E. M. F. for both alternations of one cycle. It is therefore necessary to find the *effective* value of this E. M. F., and this is done by letting it expend its energy in heating a given resistance that is devoid of self-induction. The same resistance is then exposed to the heating effect of a direct-current E. M. F., and that value of the latter which was required to produce the same effect is taken as the equivalent of the alternating E. M. F. The same procedure is followed when measuring the alternating current. Its rate of flow is constantly changing, and therefore difficult to determine. But its heating effect may be determined and compared with

that of a direct current; we then have what is termed the *effective* current-strength.

When the effective E. M. F. of an induction-coil is known, it gives but little information about the range of E. M. F. which in reality exists. The effective pressure may, for instance, be 10 volts, and yet the E. M. F. produced by the coil may vary between 50 volts and zero. Fortunately it is of little importance to know the effective E. M. F. or amperage of this induced current when used for therapeutic purposes. In recording the treatment of patients, and in communications to medical literature, the effective E. M. F. and amperage would be of real scientific service. The pressure and current-strength are determined by the condition of the individual under treatment, and may vary within wide limits. It is of more importance to have means for *regulating* the pressure to suit individual treatment than to *know* the real current-strength. This applies to the treatment of an individual patient, and not to the contributions that go to make up the real progress of electrotherapeutics. This is not supposed to mean that *any* coil combination will do, as long as its current-strength is adjusted to a certain value. It is taken for granted that the operator is able to foretell the general effects of the various combinations that his apparatus will allow, and that subsequently only smaller variations will be required to suit individual cases. This is usually effected by means of a variable resistance, as already mentioned in Art. **101** describing Fig. 62. A resistance will make it possible not only to vary the current-strength between very wide limits, but also to prevent sudden fluctuations when changing from one combination to another. It will further enable the operator to effect gradations of the E. M. F. so small as to be almost inperceptible. In short, it places the induction-coil completely under his control. The various means for interposing such resistances in the circuit will be described in another Paper.

ELECTROSTATICS.

ELECTROSTATICS.

ELECTRIFICATION.

1. Positive and Negative Electricity.—In the previous Papers of this Course we have considered electricity in motion. When an electrification takes place on a substance that is able to conduct electricity, the latter will at once be distributed throughout such a substance and cause a flow, or current. In case the substance is *not* a conductor the various electromotive forces that may have been produced on the substance have no opportunities for equalizing themselves, and the charge will remain where it was produced.

When a body is in this state it is customary to say that it is *positively* or *negatively* electrified, meaning thereby that in the former case a current would flow *from* the body, and in the latter case *into* it, if a conductor were brought in contact with it. This property of a non-conductor by which it is able to retain an E. M. F. in a condition, so to say, dormant, but ready to send a current in one direction or other, depending on whether its potential is positive or negative, has given rise to the idea that there are two kinds of electricity, positive and negative. It is then supposed that ordinarily, when a body is in a neutral condition, these two kinds are mixed, but that after electrification has taken place the positive would separate from the negative and form two distinctive kinds of electricity, different in character and tendency. These two kinds would eagerly seek to unite with each other and again produce a neutral condition.

We are here in the same position as when we were considering the flow of a current. It was then remarked that, if a flow of electricity really took place, we were not certain in which direction it actually was flowing. A current might possibly flow from the body of lower to that of higher potential, or

might flow from both simultaneously, or not flow at all. In any case, we preferred to speak of the equalization of different potentials as causing a *current* of electricity, as this made it easier to describe the various phenomena and to formulate rules and laws.

2. The same holds true with the phenomena of static electricity. When two bodies are respectively positively and negatively electrified, there is a mutual action between them, which seems to be similar to that taking place between two magnetized bodies. Moreover, the forces seem here to act along lines of force, and to cause attraction or repulsion, as the case may be; also, we must here suppose the *ether* to be the medium that transmits the forces from one body to the other. Notwithstanding these facts, we prefer to speak of positive and negative electricity, because it makes it much easier to explain the phenomena of static induction and the action of static induction-machines. When, therefore, in the following pages, we speak of positive and negative charges, it must not be taken for granted that such charges actually exist, but that on the contrary these terms are simply used for convenience, as, without them, it would be almost impossible to describe the phenomena of static electricity to one not familiar with the science of electricity.

3. Charge.—When a body has been submitted to some influence that has changed its neutral condition into one in which a difference of potential has been created, either between different parts of the same body or between different bodies, the body is said to have been electrified, or to have been *charged.*

The one part or body that possesses a positive potential is said to be positively charged; the other, negatively. *It is impossible to bring forth one charge without bringing forth another of equal quantity.*

4. Conductors and Insulators.—If an electric charge is communicated to one end of a glass rod it will remain there, and will not pass to the other end of the rod. The glass rod will not permit the charge to spread through its substance, because it is a non-conductor, or what is called an *insulator.*

If, on the other hand, a metal rod receives an electric charge at one end, the charge will immediately distribute itself over the whole rod. The metal rod, unlike the glass rod, *conducts* the charge from one portion of its surface to all other portions, and is therefore called a *conductor*. A substance that is an insulator is said to offer a great *resistance* to the flow of electricity through it, but it must not be supposed that conductors offer no resistance. The fact is, there is no substance so good an insulator as not to allow some electricity to pass, and there is no conductor that does not possess some resistance; no sharp distinction can be drawn.

In the following list various substances are placed in the order of their conductivity.

Good Conductors	Silver Copper Other metals Charcoal Water The human body, except the dry skin
Semiconductors	Cotton Dry wood Marble Paper Alcohol Ether Powdered glass Ice at 32° F.
Non-Conductors, or Insulators	Oils Porcelain Wool Silk Resin Gutta-percha Shellac Paraffin Glass Dry air

FRICTIONAL ELECTRICITY.

5. Both Bodies Conductors.—The means employed for electrifying bodies depends somewhat on their nature—whether they are conductors or non-conductors. In the case of two conductors, by merely bringing them in contact a positive charge is produced on one and a negative charge on the other. The amount of charge so obtained may, however, be very slight, and requires delicate measuring instruments to detect it.

6. One or Both Bodies Insulators.—When one or both of the bodies are insulators, or non-conductors, it is necessary that one of them be brought in energetic contact with the whole surface of the other, or as much of it as is to be electrified. This is usually done by rubbing one body intimately with the other, as, for instance, a silk handkerchief with a glass rod, or a piece of cat's fur with a stick of sealing-wax. When the bodies are separated, after rubbing, each will be found to be charged—one positively, the other negatively. The friction between the two substances simply causes contact between their various parts, and the charge should therefore be considered of the same nature as that generated by contact between two conductors. The difference between the two cases is that, in the case of the conductors, the charge flows to all parts of the body, while, in the case of the non-conductors, the various parts have to be charged separately by contact.

7. Energy of Charge.—The amount of electric energy stored up on either of the bodies is not proportional to the work done by friction, but only to the small work done in separating the two bodies against their mutual attraction.

8. Conditions for Electrification.—It was formerly thought that only a limited number of substances could produce an electric charge when brought in contact with each other; but later investigations show that friction between any two different substances, no matter what the substances may be, always produces a separation of positive and negative electricity. It is not even necessary that the substances should be different, as two bodies of the same substance, one with a smooth and the other with a rough surface, will show a charge when rubbed together. In this instance, the body whose particles are more easily removed shows negative electricity. Two bodies of the same substance with different temperatures will show electrification, and it has also been shown that two bodies of the same substance, but of different colors, will in some cases be electrified when rubbed together. Whether the bodies are brought in contact by means of either rolling or sliding friction seems immaterial. The main thing seems to be to bring the various

parts of the surface of one body successively in contact with the surface of a dissimilar body, and separate them, in order to produce a charge. Static electrical machines are based on these principles, and the following experiments, some of which may appear quite elementary, are made for the purpose of making the action of electrical machines, belonging to either the friction or the induction system, perfectly clear.

9. Conditions Governing Kind of Charge.—Let us now consider the conditions necessary for producing an electric charge on a body, and the means of detecting its presence and kind. Evidently this latter feature is a very important one, as all of these phenomena can be studied only by the most careful use of the testing instruments, both as regards the correct interpretation of the action taking place, and also in preventing exterior forces from interfering with the forces under observation.

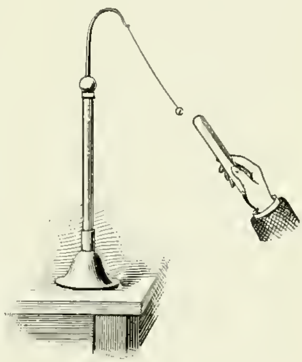

FIG. 1.

By rubbing a glass rod with a piece of silk, the rod will receive a charge that it has been agreed to call *positive;* the charge on the silk will, therefore, be *negative.* The presence of the charge can be detected by holding the glass rod in the neighborhood of light bodies, such as chaff or small bits of paper; it is seen that these small particles are attracted by the rod, and, after contact with it, partake of its charge and are repelled.

10. The Electric Pendulum.—A more suitable apparatus for studying these actions is an *electric pendulum*, as represented in Fig. 1. It consists of a glass rod supporting a metal bracket, which carries a silk thread to which is attached a pith-ball. If the glass rod is held near the ball, it will be attracted by the rod, and then, having partaken of its charge, be repelled. Now, by rubbing a stick of sealing-wax with a piece of fur, a charge will be given to the stick, and if it is held near another pith-ball, the ball will also be attracted, and after contact

repelled. As these two rods have the same effect on two separate pith-balls, it would naturally be supposed that they would be charged with the same kind of electricity; but let us now see the effect of holding the sealing-wax near the pith-ball repelled by the glass rod. It will be attracted, and after contact repelled, and the same will take place if the glass rod is held near the other ball. Evidently the two charges must be of a different nature, and, if the glass rod is *positive*, the sealing-wax must be *negative*.

As another experiment, touch one of the balls with the charged glass, and the other with the charged sealing-wax. Now bring the two balls into proximity; it will be found that there is an attraction between them. Again, charge both balls from the glass rod, or both from the sealing-wax; in each case the balls will repel each other.

11. It was stated that two substances rubbed together will have different charges, so that, when the glass rod is positive, the silk should be negative. The pendulum will prove this, because, after the ball has been attracted and repelled by the glass rod, it will be attracted anew by the silk. If, again, the electricities of these two bodies is imparted to a third body, the latter will have no effect on the pendulum, proving that both electric charges have united and neutralized each other.

We deduct from these experiments the following laws:

1. *When two dissimilar substances are placed in contact, one of them always assumes the positive and the other the negative charge.*

2. *Electrified bodies with similar charges are mutually repellent, while electrified bodies with dissimilar charges are mutually attractive.*

These are two of the most important laws in the study of electricity.

12. The Electric Series.—As has already been stated, glass rubbed with silk will receive a positive charge. Such a charge was formerly called *vitreous*, under the erroneous impression that this was the only kind of charge glass was capable of yielding. It is found, however, and can be easily proved by the electric pendulum, that glass rubbed with fur will receive a

negative charge. Sealing-wax or resin rubbed with silk will, as has been pointed out, take a negative charge, and for this reason a charge so obtained was called *resinous* electricity. If, however, wax or resin is rubbed with gutta-percha, the former will take a positive charge, proving that these substances are capable of receiving either a positive or a negative charge. It will thus be seen that the character of the charge depends equally on the material composing the two substances rubbed together.

The following list, called the *electric series*, gives the various substances in such an order that each receives a *positive* charge when rubbed with any of the bodies following, and a *negative* charge when rubbed with any of those which precede it:

1. Fur	6. Cotton	11. Sealing-wax
2. Flannel	7. Silk	12. Resin
3. Ivory	8. The human body	13. Sulfur
4. Crystal	9. Wood	14. Gutta-percha
5. Glass	10. Metals	15. Guncotton

13. Charges on two bodies may differ not only in kind, but also in amount. If a charged body is brought in contact with a larger body not charged, or charged with the opposite kind of electricity, there will be a redistribution between the two bodies. If the charges are equal and opposite, no charge will remain on either. If the charges are of opposite kind and unequal, then the smaller will be neutralized by an equal amount of the larger, and the remainder of the larger charge will distribute itself over the surfaces of both bodies. The speed with which this distribution takes place depends on the substance of the body; if a good conductor, it will be practically instantaneous; if an insulator, it will be slow, and will take appreciable time.

MEASUREMENT OF CHARGE.

14. The Gold-Leaf Electroscope. — For very crude tests, the electric pendulum may be sufficiently accurate, but, when finer measurements are needed, an instrument will be required that is capable of indicating minute charges, and at

the same time is shielded from the moisture and motion of air. Such an instrument is the *gold-leaf electroscope*, illustrated in Fig. 2.

A brass wire *x*, the lower end of which is bent so as to support the two gold leaves *a*, is passed through a glass tube *b*, projecting through a well-varnished cork closing the mouth of a glass jar *J*. The upper part of the brass wire is provided with a flat disk, or plate *c*, of conducting material. This instrument not only shows whether a body is electrified or not, but can also be made to show the kind of electricity with which a body is charged.

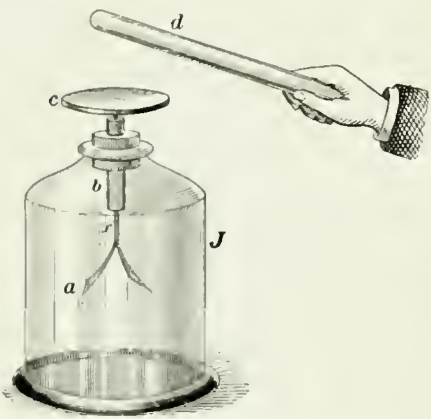

FIG. 2.

Let us rub a glass rod *d* with silk, and hold it in the neighborhood of the disk *c*, without making actual contact. The gold leaves will diverge. The glass rod we know to be positively electrified, and, when it is brought near to the disk *c*, a separation of the electric fluid in the metallic portions of the electroscope takes place, the negative electricity being attracted to the plate *c* by the positive charge on the glass rod *d*, and the positive charge being repelled to the gold leaves. This charges the two gold leaves positively, and, as similarly-charged bodies are mutually repellent, they are caused to diverge. If the rod is withdrawn without touching the plate *c*, the positive and negative charges on the electroscope reunite, thus allowing the gold leaves to come together. The action described, causing a separation of the two electricities in a body by the proximity of a charged body, is called *induction*, and is treated at greater length in Arts. **20**, *et seq.*

Again bring the rod near the electroscope, and this time touch the plate *c*. On removing the rod the leaves remain diverged,

because some of the charge on the rod is imparted to the electroscope. This charge is of course positive, and causes the gold leaves to remain diverged until the charge is removed. Knowing the character of this charge, we are able to compare other charges with it and find out whether they are of the same or of a different kind.

Let the glass rod be rubbed with flannel. The question now to be answered is whether the rod is charged with positive or with negative electricity. On bringing it near to the disk on the electroscope, the leaves show a tendency to close together. This is evidently because there is less repulsion between them; that is, their positive charge must have become less. Evidently, then, the rod must be negatively charged, so that it attracts a part of the positive charge on the leaves towards it, leaving them less strongly charged. On the other hand, if the rod were positively charged, the gold leaves would spread wider apart, because the positive charge on them would be made stronger.

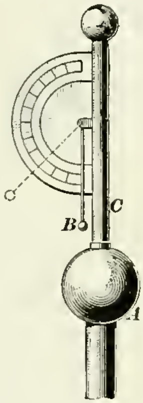

FIG. 3.

From the foregoing we may draw these conclusions:

If the gold leaves diverge, the body being tested has a charge of the same kind as that on the electroscope. If the gold leaves approach each other, the charge is of the opposite kind.

15. Quadrant-Electroscope.—When it is desired to indicate and measure very large charges, an instrument called the *quadrant-electroscope*, shown in Fig. 3, is used. A is a conductor on which the charge to be measured is placed. It is provided with an upright rod C on which the electroscope is mounted. B is a pith-ball, supported by a light arm pivoted on the upright rod. When the conductor A is charged, the ball will be repelled in proportion to the charge, and a graduated scale will indicate the angle of divergence.

16. Torsion-Balance.—Both in the electric pendulum and in the electroscope, we have seen forces at work repelling similarly-charged bodies. The magnitudes of these forces under

varying conditions are as yet unknown to us, and it is desirable to examine them a little closer. None of the instruments so far mentioned will do this with any accuracy, and some other means must be provided. This we find in the *torsion-balance*, a combination of an electric pendulum and an electroscope. In Fig. 4 a light arm of shellac is provided with a gilt pith-ball n suspended from the movable head b by means of a fine silver wire. Another gilt pith-ball m is fastened to the end of a glass rod a, which can be inserted through an opening in the cover of the glass cylinder. Around the cylinder, on a level with the pith-balls, is a graduated circle. The head b is called the *torsion-head*, and is also graduated, and its angular motion is indicated by means of an index on a fixed arm near it.

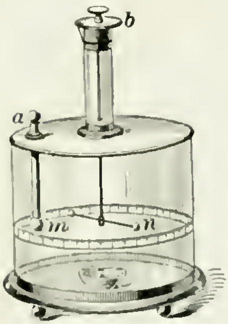

FIG. 1.

To measure the amount of an electric charge, we proceed as follows: The torsion-head is turned until the balls just touch each other; the glass rod is removed and a charge imparted to the ball m, and the rod is then replaced. As n is uncharged, it will receive part of the charge on m, and the two balls will mutually repel each other; n will recede and produce a certain twist in the silver wire. When the repelling force is counterbalanced by the twisting force, the arm will come to rest. As the angle through which a wire is twisted is precisely proportional to the force with which it is twisted, it follows that the force of torsion is proportional to the angle of torsion. If the angle through which the ball moves is not too large, the ball will practically move in a straight line, and it may therefore be said that the force of torsion is proportional to the direct distance between the balls.

17. Law of Inverse Squares.—By means of the torsion-balance it is possible to prove that *the force exerted between two small bodies, statically charged with electricity, varies inversely as the square of the distance between them.* Thus, if two electrified bodies, 2 inches apart, repel each other with a certain force, this

force will be four times greater if the distance between them is decreased to 1 inch. This law holds good for both repulsion and attraction, and also when the charges on the two bodies are of unequal amounts. At a given distance, the attraction or repulsion between two bodies will be *proportional to the product of the two quantities* of electricity with which they are charged. For instance, if one body is charged with 5 units, and another with 3 units of electricity, the force acting between them will be $5 \times 3 = 15$ times greater than it would be if each body had received but 1 unit.

18. Unit Quantity.—A unit quantity of electricity is that charge which, when placed in air at a distance of 1 *centimeter* from another equal and similar charge, will be repelled with a force of 1 dyne. The *dyne*, or unit of force, is that force which, by acting on a mass of 1 gram for 1 second, can give to it a velocity of 1 centimeter per second.

19. The Coulomb.—There is another unit of quantity, based on what is called the electromagnetic system of units. This is called the *coulomb*, and its value is 3,000,000,000 times that of the electrostatic unit.

ELECTROSTATIC INDUCTION.

20. We have seen that, when electricity has been transferred from one body to another by actual contact, an attraction or repulsion will take place ; but we have also seen, when mention was made of the gold-leaf electroscope, how a charge could be present on the gold leaves when no actual contact had been made with charged bodies. This latter phenomenon is perhaps the most important one in static electricity, and deserves a great deal of attention.

21. The Electrostatic Field.—It is accepted as a matter of fact that an electrified body can have no influence on a body not charged with electricity. How, then, can we explain why a neutral pith-ball is attracted by a rubbed glass rod? The answer is that, before any attraction takes place, the glass rod

has, while some distance away, caused a division of the neutral state of the ball into positive and negative electrification, so that a negative charge has collected on the side next to the glass rod, and has therefore been attracted. All this will take place almost instantaneously, but, before the positive and negative charges have been established, no attraction will be noticed. This influence, which a charged body is capable of exerting on a neutral conductor, is called *induction*, and the charge is called an *induced* charge. The range of space in which it takes place is an *electrostatic field*. We recognize here conditions very similar to those explained under magnetic induction.

22. The apparatus shown in Fig. 5 illustrates this phenomenon more fully. C may be a glass ball charged with positive electricity, and $A\,B$ a conductor with no charge, both insulated from the ground by glass columns. When C is placed in the neighborhood of $A\,B$, electric charges are induced on the conductor, and it is found that its two ends have charges of opposite kinds. The pith-balls suspended from the conductor will also show that the charges are not uniform, because the former are seen to diverge more and more, the farther they are from the center of the conductor; in fact, the middle part will show no charge whatever. It is also found, by testing with an electroscope, that the end A is charged with negative and the end B with positive electricity. Should the ball C again be removed, we see that the pith-balls touch each other; the charges have, therefore, entirely disappeared. They have neutralized each other, and therefore must originally have been present in equal amounts. The conductor may be made in two parts and separated before the ball C has moved away, in which case each part will have a charge of an opposite kind.

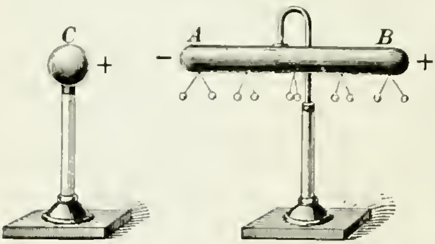

FIG. 5.

From this experiment we draw the conclusions that a positive

charge attracts a negative charge and repels a positive one, and vice versa, and that this influence can take place through some distance and through materials such as air, glass, etc.; that, when the electrified body is removed, it will again return to its natural condition, and that the inducing body has lost none of its charge.

If the body on which the charge is induced has connection with the ground, the results are somewhat different. Let the bodies occupy the position illustrated in Fig. 5. If, now, a connection is established between *A B* and the ground by touching it anywhere along its surface, even at *A*, the positive charge will escape and be neutralized in the ground, and the negative charge only will remain. The charge that passed to the earth is called a *free* charge, while that charge which is held by the inductive influence of *C* is called a *bound* charge. On the removal of *C*, the induced negative charge is released; it is also *free*, and will now distribute itself over the whole surface of the conductor.

23. There is yet another modification of these experiments to be considered. The smaller the distance between the two bodies, the stronger the induced charge will be; it would eventually be equal to that on the charged body. Before this position could be reached, however, the insulating capacity of the intervening substance (in this instance air) would break down, and the charges rush across and reunite with such avidity that a spark would be seen between the bodies. The negative charge at *A* and the positive at *C* have now reunited, and have by that act neutralized each other. The bound charge at *B* is now free, and positive electricity is distributed all over *A B*.

In the latter experiment, the induced negative charge was supposed to be of equal quantity with the inducing positive charge; by their union they would therefore neutralize each other. Should the charges on two bodies not be of equal amount, there will remain, when they combine, a surplus of a kind depending on which charge predominated. Thus, if one body is charged with 50 units of positive and another with 30 units of negative electricity, their union will result in the

neutralization of 30 units of each charge, leaving 50 − 30 = 20 units of positive electricity; and this quantity will divide itself, giving each body a positive charge of 10 units, provided the bodies are of equal size and of the same shape.

24. Inductive Capacity.—It is not unimportant what substance is residing between two charged bodies, as some substances permit the induction to take place with greater facility

Material.	Inductive Capacity.
Air, vacuum at about .001 millimeter pressure	.9400
Air, vacuum at about 5 millimeter pressure	.9990
Hydrogen, at ordinary pressure	.9990
Air, at ordinary pressure	1.0000
Carbon dioxid, at ordinary pressure	1.0005
Olefiant gas, at ordinary pressure	1.0007
Sulfur dioxid, at ordinary pressure	1.0037
Paraffin, clear	1.92–2.47
Petroleum	2.03–2.07
Turpentine	2.16
India-rubber, pure	2.34
India-rubber, vulcanized	2.94
Resin	2.55
Ebonite	2.56–3.15
Sulfur	2.88–3.84
Shellac	2.95–3.73
Gutta-percha	4.20
Mica	5.00
Flint glass, very light	6.57
Flint glass, light	6.85
Flint glass, very dens	7.40
Flint glass, double extra dense	10.10

than others. *Dry air offers more resistance to induction than any other substance.* The facility with which a substance allows electrostatic induction to take place across it is called its *inductive capacity*, and the substance itself is called a *dielectric*. An insulator and a dielectric are not necessarily the same thing; a good insulator may be a poor dielectric, but all dielectrics are insulators. There is this distinction between them, that the

more resistance a substance offers to the passage of an electric current, the *better insulator* it is, while the *less* resistance a substance presents to an inductive influence across it, the better *dielectric* it is said to be. A good dielectric is said to possess a *high* inductive capacity.

The preceding table gives the inductive capacity of various substances, the capacity of air at ordinary atmospheric pressure being taken as unity.

25. The Electrophorus.—The amount of electrification that can be produced by rubbing a glass rod is rather limited, and, in order to produce larger charges on other bodies, the use

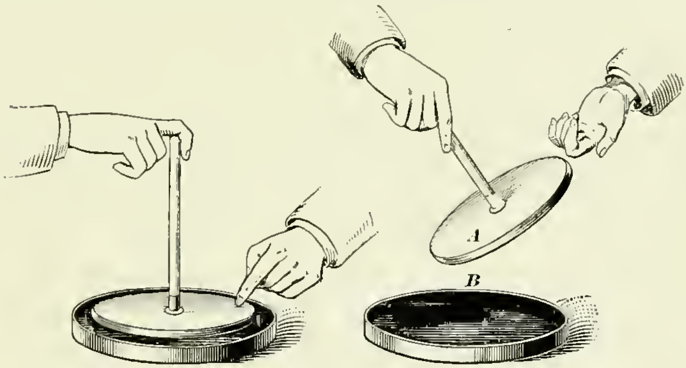

FIG. 6.

of some other apparatus becomes necessary. This is found in what is called an *electrophorus.* By means of this instrument an almost unlimited number of static charges of electricity may be obtained from one single inducing charge. It consists of two main parts (Fig. 6), one a round cake of resinous material cast in a dish, or pan B, about 1 foot in diameter; and a disk A, slightly smaller, made of metal, or of other material, covered with a conducting substance, and provided with a glass handle. In modern instruments, B is usually made of ebonite. When using the electrophorus, the resinous cake must first be beaten or rubbed with a warm piece of woolen cloth or fur. The disk, or cover, is then placed upon the cake, touched momentarily with the finger to liberate the free charge, then

removed by taking it up by the handle. It is now found to be powerfully electrified with a positive charge, so much so, indeed, as to yield a considerable spark when the hand is brought near it. The cover may be replaced, touched, and again removed, and will thus yield any number of sparks, the original charge on the resinous plate meanwhile remaining as strong as ever.

If the previous experiments in induction have been well understood, it should not be difficult to see the reason for these phenomena, and, as they serve as a basis for electrostatic machines, it is important that they appear perfectly clear before we proceed any further.

After the cake has been beaten with the fur, its condition is that of Fig. 7; it is charged with negative electricity. When the disk A is approaching the cake, the latter will act inductively on the disk, and attract a positive charge on its lower side and repel a negative charge to its upper side. These charges will increase in amount until they reach a maximum, when

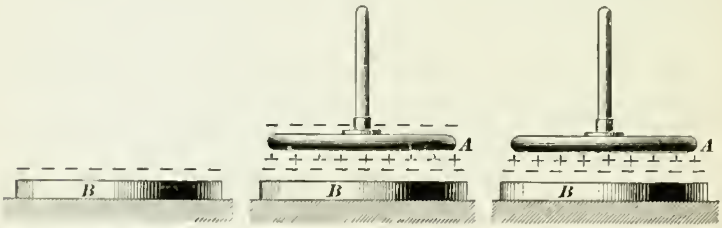

FIG. 7 FIG. 8. FIG. 9.

contact is made with the cake. This condition of cake and disk is represented in Fig. 8. Should the disk be now touched, the free negative charge will be neutralized by electricity flowing through the observer's body to earth, while the positive electricity will remain as a bound charge, as shown in Fig. 9. The disk can now be lifted, when the positive charge will be no longer bound, and will distribute itself all over the disk, as illustrated in Fig. 10.

The charges given to the disk will not diminish the original charge on the cake, as the action is purely inductive, and the recharging of the former could go on forever if the cake were not subjected

to a certain amount of leakage through the atmosphere, particularly when the air is damp. The charge must therefore be replenished at certain intervals. If a metallic stud is fastened to the bottom of the pan B, so as to project through the cake near its surface, a spark will pass between the stud and the lower side of the disk when this is laid down on the cake, and the negative electricity will be automatically discharged, thus dispensing with the necessity of touching the disk before removal.

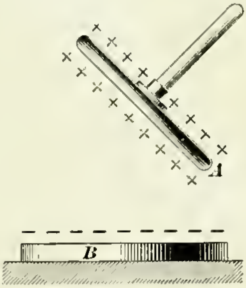

Fig. 10.

It was remarked above that, were it not for the leakage from the cake through the air, the charging and discharging of the disk could go on indefinitely. Evidently, the supply of energy represented by each charge must be drawn from some source, and it is of some interest to inquire into its origin. The fact is that, when the disk is removed from the cake, after being charged, it offers more resistance against its removal than when it was neutral. This supply of muscular energy is the real measure of the energy dissipated in each discharge of the disk.

POTENTIAL.

26. Change of Potential.—The experiments with the electrophorus do not exhaust all the possibilities of inducing charges in neighboring bodies, and it will be necessary to consider some further modifications. These can best be observed by means of the two disks shown in Figs. 11, 12, and 13, where A is a metal plate insulated from the ground, and B another metal plate provided with a glass handle.

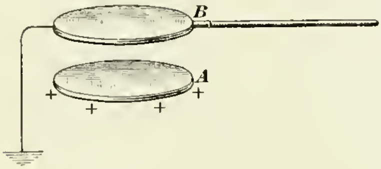

Fig. 11.

Let it be understood that, when mention is made in the following of positive or negative potential, it will mean the potential of the *free* charge on a body subject to induction, a charge that would flow to earth if opportunity were given it.

The various combinations and modifications will be found in the following table, with the resulting potential, density, and charge, the number in the table corresponding to the numbers of the following divisions :

1. Let A, Fig. 11, be charged with positive electricity and be without any connection with the ground.

2. A neutral disk B in metallic connection with the ground is brought near A in the position shown in Fig. 11 ; the positive charge is drawn towards B away from the lower side of A.

3. Let B be brought still nearer to A, and more charge will be drawn towards B, decreasing the density on the *lower* side still more.

4. If now A and B are separated again, the condition of both will be as it was before.

5. Now let B also be *positively* charged and placed in the position of Fig. 12, without connection with the ground. The

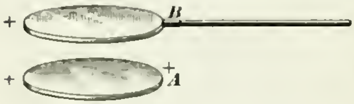

Fig. 12.

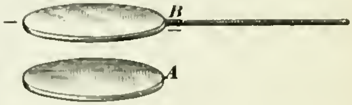

Fig. 13.

density on the *lower* side of A is increased ; the charge is, so to speak, driven away from the upper side.

6. Let B be brought still nearer to A, and the charge on the lower side will increase.

7. While B is in the last position, let A be connected with the ground ; its positive charge will escape, it will have a bound negative charge, and the potential will be zero.

8. Disconnect A from the ground and remove B ; the negative charge will be free and spread itself all over A, and there will be a negative potential.

9. Next let A be *neutral* and insulated from the ground, and B, a negatively-charged body, as shown in Fig. 13. Then the potential of A will be negative, because negative electricity would escape to the ground if it were connected with it. The density on the upper side is positive ; on the lower, negative.

10. Without changing the position of either body, let A be

connected with the ground, when its potential will be zero and its charge positive.

11. Disconnect A from the ground, and separate A and B slightly; the potential of A is then positive.

12. Let B come nearer to A than it did in position 10; then the potential of A becomes negative, because negative electricity would escape from A if connected with the ground, but the charge is positive, as before.

The conditions of conductor A during these experiments are shown in the following table:

CONDITION OF CONDUCTOR A.

Number.	Potential.	Density. Upper Side.	Density. Lower Side.	Charge.
1	Positive	Positive	Positive	Positive
2	Positive, but less than in 1	Positive, but greater than in 1	Positive, but less than in 1	Positive
3	Positive, but small	Positive, and still greater than in 1	Positive, but less than in 1	Positive
4	Positive	Positive	Positive	Positive
5	Positive, but greater than in 1	Positive, but less than in 1	Positive, but greater than in 1	Positive
6	Positive, and still greater than in 5	Almost none	Positive, and still greater than in 5	Positive
7	Zero	Negative	None	Negative
8	Negative	Negative, but less than 7	Negative	Negative
9	Negative	Positive	Negative	None
10	Zero	Positive, and greater than 9	None	Positive
11	Positive, but small	Positive, but less than 10	Positive, but small	Positive
12	Negative, but small	Positive, but greater than 10	Negative, but small	Positive

27. We see, from the interesting phenomena in Nos. 10, 11, and 12, that, by a small motion of B either to or fro, the potential of A is changed from zero to either positive or negative. To make this still clearer, let us repeat the last experiments on the electroscope in Fig. 14.

Let B be given a negative charge and A be neutral; when B is separated from A by a distance d, connect A for a moment with the ground and again insulate it. The negative charge will then have escaped and the potential is zero; the gold leaves will therefore not diverge. Remove B to a distance a little greater than d, and the gold leaves will diverge with positive electricity, because the potential of A is now positive.

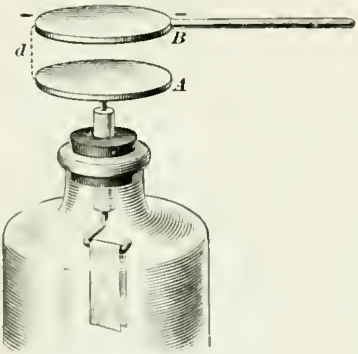

FIG. 14.

Bring B a little nearer than d, and the gold leaves will close and immediately diverge again with negative electricity; the potential is now negative.

28. Conditions Governing Potential.—From these experiments we have seen the influence of the electric charge on the potential of a conductor, and it has been noticed that the potential depends on the sign and amount of the free charge. The experiments, particularly the last three, have also demonstrated that the potential of a conductor depends on its position in relation to other bodies.

It now remains to investigate the influence the shape of a conductor has on its potential. To do this we will again use the apparatus in Fig. 14. Let B be laid on A and a charge given to them while in contact; they will then act as one conductor, and the gold leaves will diverge in proportion to the charge given them. It is now found that, on sliding B on A, or lifting one side of B without separating them, the divergence of the gold leaves will increase. On putting B back into its original position, the divergence of the gold leaves regains its original value, proving that the alteration of the form of the compound body $A\,B$ alters its potential without altering the amount of electricity on it.

From all this we finally draw the conclusion that the *potential*

of a *conductor* can be varied (1) *by altering the charge of electricity on it;* (2) *by altering the external shape of the conductor without altering the charge of electricity on it;* and (3) *by altering its position relative to other bodies.*

29. Location of Charge.—The preceding experiments also make it clear that the *electricity at rest* resides only on the surface of a conductor, and, so long as we have to do with electricity at *rest*, it is immaterial whether the conductors are of solid or of hollow metal, or whether they are simply made of wood and coated with tin-foil or gold-leaf. It may be well to give some additional proof of this assertion, which may be done in several ways.

Let, for instance, a hollow metal ball with an aperture at the top be supported on an insulating stem and a charge given to the ball. In order to examine the density of the charge on various parts of the conductor, use is made of what is called a **proof-plane,** a little disk of sheet copper fixed to the end of a glass rod. If this disk is laid on the surface of an electrified body, part of the electricity flows into it, when it may be removed and its charge examined with an electroscope. Such a proof-plane, if applied to the surface of an electrified ball and then brought in contact with the knob of an electroscope, will cause a divergence of the gold leaves, showing the presence of a charge. If, now, the proof-plane is inserted through the aperture and touched against the inside of the globe and then withdrawn, it will be found that the inside shows no sign of electricity. Even a cylinder made of wires interwoven with one another will show no sign of electricity on the inside, if the meshes are not too large.

If two hollow hemispheres of copper are placed together over a charged copper ball without touching it, the inner ball will retain its charge only so long as it is not touched, but when it is touched the charge will instantly pass to the exterior ball, and the inner ball is, on removal of the outer, found to be completely discharged. This tendency of a charge to rest only on the outside was shown in a most striking way by Faraday. A conical bag of linen gauze was supported upon an insulating

stand, and a silk string attached to its apex by means of which it could be turned inside out. When charged, the electricity was found to reside on the outside, and, when the bag was turned inside out, the charge was again on the outside, leaving the inside without a trace of electricity.

30. Exceptions.—There are a few exceptions to the law that electricity always rests on the outside of a conductor.

1. The presence of an electrified body inside a hollow conductor acts inductively on the latter, and attracts an opposite kind of electricity to the inside of the conductor.

2. Electricity in *motion* does not flow on the surface only, but through the substance of the conductor. This law is therefore limited to an electric charge only.

In medical practice, physicians employ a type of electrical apparatus called a *static* machine, and the *current* that it produces is called *static* electricity, without reference to the scientific term *electrostatics*, which has an altogether different meaning. The foregoing experiments with electrostatic charges have done much to confuse the therapeutics of static electricity in current form. The error arises from the use of the word *static*, which seems to imply that the charges produced in a static machine are at rest, and as such do not act as an ordinary current. But the electrostatic charges produced in these machines are mostly allowed to unite, and will therefore produce a current of electricity. For medical use these charges are always set in motion, and cannot be employed unless they are in motion. Static electricity as employed in therapeutics has no medical value while it is at rest; hence, the proposition that a static charge resides only on the surface of a body cannot apply to the treatment of a patient with a current which is not at rest. It is demonstrated that all methods of treatment employ electricity as a current, and never as a "charge" at rest. Moreover, no one can prove that electricity resides only on the surface of a patient's body during any form of actual treatment, while every evidence tends to prove that the internal tissues are affected and traversed by the current.

The first exception may be proved by the following experiment: A in Fig. 15 is a hollow conductor, in metallic connection with the electroscope B; C is a metallic ball with a positive charge. When the ball is lowered into A, a negative charge is attracted to the inside of the conductor and a positive charge repelled to the outside. The gold leaves will diverge more and more with a positive charge, until the ball is well inside the conductor, when they remain stationary. If contact is now made between the ball and the inside of the conductor, no

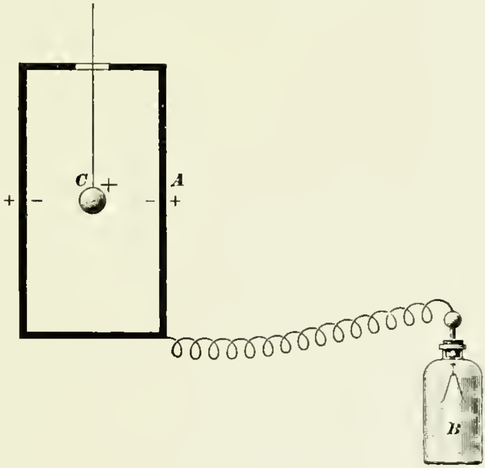

FIG. 15.

effect will be noticed on the gold leaves, which proves that the charge on the inside of the conductor and that on the ball are precisely equal in amount, but of opposite signs; when united they will therefore neutralize each other, and leave the positive charge on the outside, as before. This hollow conductor, or *electric cage*, as it is sometimes called, affords a very ready means for comparing and examining charges on small bodies. They need not be discharged, but simply lowered into the cage; and the induced charge repelled to the outside will be of the same sign and quantity as the inducing charge, and can therefore readily be examined by means of the electroscope.

31. Distribution of Charge.—A static charge of electricity is not usually distributed uniformly over the surface of

conducting bodies. Experiments show that there is more electricity on the edges and corners of bodies than on the flatter parts. A charged sphere, if not exposed to the inductive influence of any surrounding bodies, will have the electricity evenly distributed all over its surface; that is, its density is uniform. The density on two similarly-charged spheres in contact with each other is found to be a maximum at the parts farthest from the point of contact, and a minimum in its neighborhood. If the spheres are of unequal sizes, the charges being equal, the density is greater on the smaller sphere; in fact, a decrease in the radius of curvature increases the density until, when at last the radius is so small as to practically be a point, the density has increased to such an amount as to be able to electrify the neighboring particles of air, which are then repelled, each carrying away part of the charge with it, thus contributing to a constant loss of charge. For this reason, points are used when it is desired to secure a rapid discharge, but must be avoided on all parts of electric machinery where a charge is to remain constant.

CAPACITY OF CONDUCTORS.

32. Capacity.—The electrostatic *capacity* of a conductor is measured by the *quantity of electricity that can be imparted to it before its potential is raised from zero to unity.*

To make the meaning of electrostatic capacity clearer, let us consider the capacity of a rubber bag when it is filled with water or gas. Its cubic contents is not limited to one definite quantity; on the contrary, it can vary between wide limits, depending on the pressure to which the water or gas is subjected. By pumping more gas into the bag, under an increasing pressure, the capacity of the bag will increase and also the pressure of the gas contained in it.

A charge of electricity will act in a similar manner. The number of coulombs residing on the surface of a conductor must not be considered as a fixed quantity, depending on the extent of its surface. It is, as seen in the case of the rubber bag, also dependent on the pressure; the higher the latter, the more compressed or dense the charge may be said to be. The

smaller the above-mentioned bag is, the less quantity of gas will be required to raise the pressure; similarly with an electric conductor, the pressure will increase more rapidly if its capacity is small. A small conductor, such as an insulated sphere of the size of a pea, will not want so much as 1 unit of electricity to raise its potential from 0 to 1, and is therefore of small capacity; while a large sphere will require a large quantity to raise its potential to the same degree, and could therefore be said to be of large capacity. It is, then, necessary to know both the capacity of a conductor and the potential of the charge before any idea can be had of the quantity of electricity collected on a given conductor.

UNIT OF CAPACITY.

33. The Farad.—If it is necessary to charge a conductor with 1 coulomb of electricity in order to produce a potential of 1 volt, it is of unit capacity, and this unit is called a *farad*. When the quantity is given in *coulombs* and the potential in *volts*, the capacity in *farads* $= \frac{\text{coulombs}}{\text{volts}}$.

EXAMPLE.—If a charge of 200 coulombs increases the potential of a conductor to 50 volts, what is the capacity of the conductor?

SOLUTION.— $\frac{200}{50} = 4$ farads. Ans.

Microfarad.—As the farad is too large for ordinary purposes, it is customary to use only one-millionth part of it, which is called a *microfarad*.

CONDENSERS.

34. Action of a Condenser.—It has been shown that opposite charges attract and hold each other; that electricity cannot flow through glass, and yet can act across it by induction. We have also seen that two pith-balls, one electrified positively and the other negatively, will attract each other across the intervening air. After interposing a plate of glass, they will still attract each other, although the electric charges on them cannot pass through the glass.

If a piece of tin-foil is fastened upon the middle of each face of a thin piece of glass, and one of the pieces is electrified with a positive charge and the other with a negative charge, the two charges will attract each other; that is to say, they are not residing on the tin-foil as *free* charges, for it will be found that on touching either of the foils practically no discharge will take place. We must therefore conclude that each charge is inducing the other—that they are *bound*. It will be found that these two plates of tin-foil may be made to receive a much greater charge in this manner than either of them could possibly receive if placed on the glass alone and then electrified. In other words, *the capacity of a conductor is greatly increased when it is placed near a conductor electrified with the opposite kind of charge.*

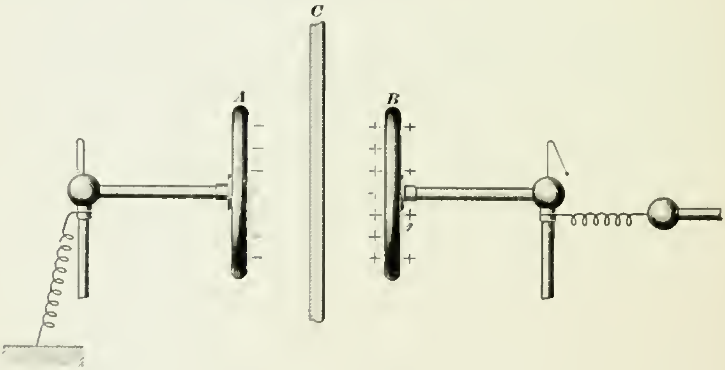

FIG. 16.

A greater quantity of electricity may therefore be put into the conductor before it is charged to as high a potential as it would be without the presence of the other conductor. Such an arrangement for holding a large quantity of electricity is called a *condenser of electricity*, or simply a *condenser*.

It is of importance to examine more closely the properties of such condensers. Let us therefore take two plates A and B, Fig. 16, interpose a glass plate C between them, and see what the effect will be when B is charged with positive electricity from some generator of static electricity and A is connected with the

ground. The positive charge on *B* will, through the glass, induce a negative charge on *A*, and repel the positive electricity to the ground. The negative charge on *A* will collect on the face nearest *B* and react on the positive charge of the latter, attracting it nearer the glass, when more electricity will be supplied from the generating source. This inducing and reinducing across the glass will continue as long as the potential of the source is able to add new charges to *B*. In fact, the effect will be the same as though a current was constantly going from *B* to *A* through a constantly increasing resistance, and then to the ground.

If the two plates are brought nearer to the glass, the attraction between the charges will increase and the inductive action will be greater; a larger quantity can therefore be accumulated on the plates. After the disks have been strongly charged, the wires may be removed and the disks brought farther away from each other. The attraction between the charges will now be less; they will be less bound, and more of the charge will be free, and able to spread over the surface. That this is so can be seen by watching the pith-balls suspended from the conductors on each side. They will diverge, giving the impression that new charges have been added to *A* and *B*, while the fact is that the capacities of *A* and *B* have diminished, giving them the appearance of being more electrified than before, because there is a greater quantity of free charge. The ground-plate *A* has the effect of greatly increasing the capacity of an insulated conductor, the surface density on the side opposite the ground-plate being very great.

It will be noticed that in Fig. 16 the pith-ball pendulums do not diverge through the same angle; this is a result of the method of charging the condenser. It is evident that, when *B* is connected to the generating source, the right side of *B* and its rod will have the same potential as the machine, while the left side of *A* and its rod will have zero potential. When *A* and *B* are disconnected from the ground and generator, respectively, *B* still retains the surplus of electricity residing on its right side, while the left side of *A* is still at zero potential; hence, the pendulums will remain as before.

35. Condensing Force.—Let us denote the total quantity of electricity on B by 1; it will be possible by induction to retain a charge on A that is somewhat smaller, which charge we will call m; $\frac{m}{1}$ will then be the ratio of the charge on A to that on B. It follows that the charge m on A should be able to bind a charge on B bearing a similar ratio to itself, which would be $m \times \frac{m}{1} = m^2$. This quantity m^2 represents, therefore, the amount of charge held or bound on B by the charge on A. By subtracting m^2 from 1 we have $1 - m^2$ as the free charge on B, a charge that can be removed by connection with the ground.

This quantity $1 - m^2$ is all the electricity that would collect on B if alone; the ratio $\frac{1}{1 - m^2}$ therefore represents the so-called condensing force acting on the plate B. The value of m is found by experiments. If it were .99, the quantity of electricity that would collect on B would be $\frac{1}{1 - .99^2} = 50$ times the quantity it would be able to keep if alone.

36. Condenser of Unit Capacity.—The capacity of a condenser is defined by the number of coulombs necessary to be given to one coating when the potential difference between the two coatings is 1 volt.

A condenser is of *unit capacity*, or of *1 farad*, when a potential difference of 1 volt between its two sets of plates charges each one of them with 1 coulomb.

37. Conditions Governing Capacity.—That the size of the coatings influences the capacity of a condenser, and is directly proportional to the same, will hardly need a proof, because a large one may simply be supposed to be made up of several smaller ones. The aggregate area of one set of coatings of the smaller condensers would be equal to the area of one of the coatings of the larger.

We have already seen that the nearer the two conductors are placed, the more intense is the inductive action between them. It can be proved experimentally that the capacity of a condenser

with plain parallel plates is inversely proportional to the distance between the coatings. We have also found that the dielectric medium plays an active part in induction, and that it is able to diminish or increase it, depending on the substance of which it consists. From this we conclude that the capacity of a condenser depends on (1) the size and form of the condensing plates; (2) the thinness of the dielectric medium between them; (3) the inductive capacity of the dielectric medium.

If the charge of a condenser in coulombs be called K, its capacity in farads F, and V its potential difference, then

$$K = F \times V \qquad (a)$$

$$F = \frac{K}{V}. \qquad (b)$$

$$V = \frac{K}{F}. \qquad (c)$$

From formula (a) we see that K may be increased by increasing either F or V, or both. When used with static electrical machines, to be described later, the potential is usually made large, while for galvanic batteries and other sources of current having low potential the capacity is increased.

38. The Leyden Jar.—When it is desirable to have a high potential difference between two charges, the Leyden jar is

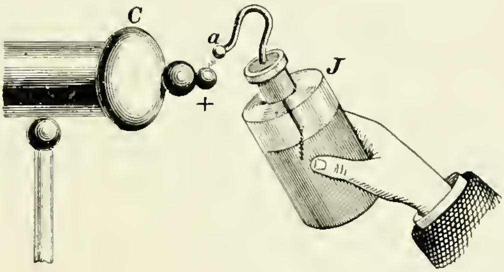

FIG. 17.

found to be a convenient form of condenser. It consists of a glass jar J, Fig. 17, coated up to a certain height on the inside and outside with tin-foil. A brass knob a is fixed on the end of a stout brass wire, which passes downwards through a lid or

stopper of dry, well-varnished wood, and is connected by a loose piece of brass chain with the inner coating of the jar. To charge the jar, the knob is held to the prime conductor C of an electrical machine, the jar being held either in the hand by the outer tin-foil, or connected to the earth by a wire or chain. When a *positive* charge is thus imparted to the inner coating, it acts inductively on the outer coating, attracting a *negative* charge to the side of the outer coating nearest the glass, and repelling a *positive* charge to the outside of the outer coating. This outer charge passes through the hand, or any conductor connected with the jar, to the earth.

This form of Leyden jar has several weak points, the main one being the difficulty of keeping the outer and inner coatings well insulated from each other. It is known that moisture collects very readily on the surface of glass, and that this, and the dust that is always liable to collect, make it possible for the electric charge to leak from the brass wire across the stopper and the outside of the jar to the outside coating.

An improvement on this form of Leyden jar is one without any wooden lid or stopper, where the stout brass rod rests directly on the bottom of the jar, thus utilizing the whole length of the inside and outside glass surface, as well as the air-space between them, as insulators.

39. A form superior to either of these is one designed by Sir William Thomson, consisting of a glass cylinder with an outer coating of tin-foil, but half filled with strong sulfuric acid, instead of having an inner coating of foil. The brass rod is here supplanted by a leaden rod expanded at its base to form a foot so as to stand firmly on the bottom of the jar. The top of the jar is closed with a wooden cover having an aperture in it to avoid contact with the rod. The sulfuric acid absorbs all the moisture that may be present inside the jar, keeping the glass in a highly insulating state, and, as the rod does not touch the cover, no current can pass except through the liquid.

40. Location of Charge.—Benjamin Franklin discovered that the seat of the charge in a Leyden jar is not on the tin-foil, but on the glass. He proved this by so making the coatings of

a jar that they could be separated from the jar after the latter had been charged. He then found that the coatings contained very little electricity. After having restored them to a neutral condition, the jar was put together again. It was now found to have a charge almost as large as before, proving that the coatings merely serve the purpose of distributing the charge over the surface of the dielectric.

41. Residual Charge.—It was also found that, after a Leyden jar had been "discharged," there remains a certain residue of charge on the glass, which after a while will emanate and collect on the surface, and will be able to give a second spark. This can be repeated a number of times, each succeeding spark becoming feebler and feebler. It is known that the dielectric between two charged coatings is subject to a certain *strain* or compression, so much so that a Leyden jar can be shown to have increased in volume, and when charged, if it is of thin glass, it may break under the strain.

42. Battery of Jars.—If the knobs and outer coatings of several Leyden jars are joined together, they will constitute what is called a *battery of Leyden jars.* The potential difference between the two coatings will be the same, but its capacity will increase in proportion to the number of jars. A battery of this kind must be handled with great care, as a shock from it may be very severe.

43. Isolated Charges.—In the preceding pages we have spoken several times about isolated charges, either positive or negative, on insulated bodies. This has been done for the sake of convenience, so as not to unnecessarily complicate the subject in hand; but if the student has taken the matter of induction well under consideration, there will by this time have been aroused doubts in his mind as to whether an isolated charge of any kind really could exist.

It has been shown that the induction between two bodies will decrease with the distance between them; from this it would be supposed that, when these experiments were performed in the limited space of a room, the surrounding objects would be subject to induction. The fact is we cannot charge one body alone—cannot place a single charge of electricity anywhere without

having an equal quantity of opposite sign somewhere else. Neither is it possible to have two bodies charged with the same kind of electricity without having a third body charged with a corresponding quantity of the opposite kind.

Let Fig. 18 represent a room *A* with two conducting bodies *B* and *C* placed therein, both charged with positive electricity. We know from our previous investigations in induction that a charge of a negative kind will be induced on the walls of the room, and that the charges on the conductors will be distributed unevenly on their surfaces, in a manner illustrated in the figure. We have said that two conductors charged with positive electricity will repel each other; it has also been quoted as a fact that two conductors oppositely charged attract each other.

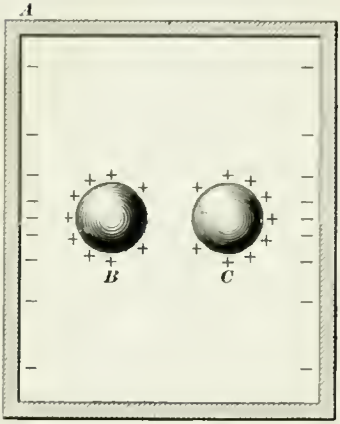

FIG. 18.

In the present instance, *B* and *C* move away from each other and tend to approach the walls; but what is the cause of this? Is it attraction or repulsion? As it has never been possible to study the behavior of two similarly-charged bodies at an infinite distance from any other bodies, it is really not known whether it is possible for two charged bodies to repel each other. It is therefore probable that, when an apparent repulsion takes place between the bodies *B* and *C*, their motion is in reality caused by an attraction between them and the adjacent walls. It will therefore be seen that every charged body forms a condenser with some other adjacent body, be it the floor, ceiling, or walls of a room, or pieces of furniture, or the experimenter himself; they all have some influence, one perhaps more than others, depending on its position or the presence of a charge on its surface. To have a charged conductor so placed that its charge will be evenly distributed, unaffected by its surroundings, will therefore be a condition very difficult to fulfil.

STATIC MACHINES.

44. As the electric charges that are obtainable from an electrophorus are rather limited in quantity and of relatively low potential, machines were early devised for the production of large electrostatic charges. There are two important types of electrostatic, or, as they are usually termed, static, maehines. The older of these machines, the *frictional* maehine, has now been almost entirely superseded by the *induction* machine.

STATIC FRICTIONAL MACHINES.

45. These machines are now obsolete, but as a description of them makes it easier to grasp the principle of the influence-machine, they will here be treated first. There are two classes of these: the *cylinder* maehine and the *plate* maehine.

THE CYLINDER-MACHINE.

46. This machine consists of three principal parts: (1) a cylinder of glass revolving upon a horizontal axis; (2) a rubber

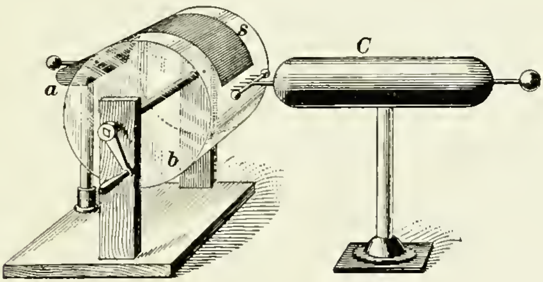

FIG. 19.

or cushion of horsehair, to which is attaehed a long silk flap; and (3) an insulated metallic eylinder called a *prime conductor*.

In Fig. 19, the cushion of horsehair a, covered with a coating of amalgam of zinc, presses against the glass cylinder b from behind, allowing the silk flap s to rest upon the upper half of the glass. The prime conductor C is provided at one end with

a row of fine metallic spikes, and is placed in front of the machine with the row of spikes projecting towards the glass cylinder. When the glass cylinder is revolved, a *positive* charge is produced upon the glass and a negative charge upon the rubber. The positive charge is carried around upon the glass cylinder, and acts inductively on the prime conductor, attracting a negative charge to the near end, and repelling a positive charge to the far end, whence it can be collected. The row of spikes is therefore strongly charged with negative electricity. The effect of charged points upon surrounding air has already been noticed; in the present instance a strong current of negatively-charged air will be driven against the positively-charged cylinder, thus neutralizing the positive charge and leaving the glass in a neutral condition, ready to be excited again. Sometimes the action of the spikes is somewhat erroneously stated to be that of drawing the positive charge from the cylinder.

When the cushion is insulated from the ground by being mounted on a glass rod, as in the present instance, the negative charge can also be collected from the brass knob, visible at the rear of the cushion.

THE PLATE-MACHINE.

47. The *plate* machine is similar in all respects to the cylinder-machine, with the exception that a glass or ebonite plate is used instead of the glass cylinder, and that there are usually two sets of rubbers or cushions instead of one. Each set of cushions is double—that is, made in two parts—with the plate revolving between them. One set of cushions is placed at the top of the machine and the other at the bottom, with silk flaps extending from each over a quadrant of the plate. The charge is collected on two prime conductors connected by a metal rod, each provided with a row of fine spikes at one end. They are placed in such a position that the two rows of fine spikes project towards the glass plate at opposite sides of its horizontal diameter. The electrostatic action of the machine is in all respects the same as that of the cylinder-machine.

Both the cylinder- and plate-machines are nothing else than machines imitating the frictional action of rubbing a glass rod

with a piece of silk, the action being made continuous and on a larger scale. As the electrical energy stored up by rubbing the glass rod and separating it from the silk was simply the work done in separating them, and not in any way proportional to the energy lost in friction, so with the frictional machines all the useful work consists simply in separating the positively-electrified portions of the rotating glass cylinder or plate from the negatively-electrified silk cushions. Most of the work expended in turning the glass plate against the frictional resistance of the cushions is completely lost in heat. The machine is therefore very inefficient, and a method had to be devised by which this large amount of friction should be eliminated. This was found in improved types of static induction-machines, which have at present completely driven the friction-machines out of the field.

STATIC INDUCTION-MACHINES.

48. Fundamental Principles.—When the action of the electrophorus was considered, it was seen that its action was founded on induction entirely. As an apparatus for delivering charges by induction it is a very good example, but one objection to it is its slowness of action. We can imagine this overcome by an arrangement in which the disk would move backward and forward between the cake and an outside contact, constantly charging the latter with positive electricity; but even then there is a serious fault inherent in the method, namely, the impossibility of raising the potential beyond that of the cake. Here it is that the great advantage of the induction-machine comes in, where it is practically possible to begin with a small initial charge, and, by adding to it little by little, increase it until at last a very high potential is reached.

The apparatus illustrated in Figs. 20 and 21 will give a good idea of the principle on which the influence-machine rests. It is mainly a repetition of the experiment with the electric cage illustrated in Fig. 15. *D* and *E* are two metallic cylinders insulated from the ground; there is a small potential difference

between them. *D* having a small positive and *E* a small negative charge. *A* and *B* are two neutral conductors, suspended by silk threads; in Fig. 20 they are shown to be in communication with each other by means of the thin wire *W* fastened to the insulating stand *C*. The following will now take place: *D* will attract a negative charge on the ball *A* and repel a positive, while *E* will attract a positive charge on the ball *B* and repel a negative. The positive charge repelled on *A* will unite with the negative charge repelled on *B* through the wire *W*, and they

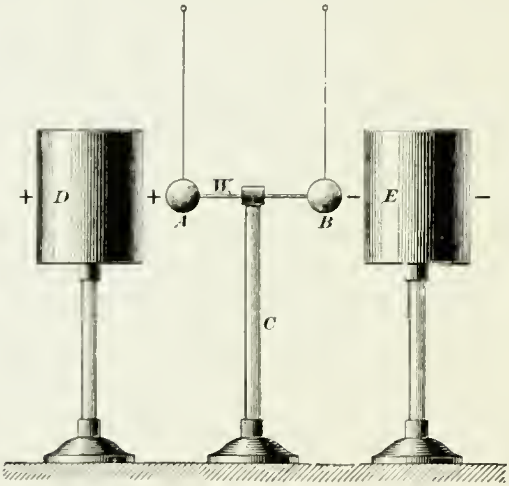

FIG. 20.

will neutralize each other, leaving a bound positive charge on *B* and a bound negative charge on *A*. If now the communication between the balls is broken by removal from the wire *W*, and *A* is inserted in cylinder *E*, and *B* in cylinder *D*, they will both induce charges of an opposite kind inside their respective cylinders, repelling a charge of the same kind to the outside, as represented in Fig. 21. When at last the balls make contact with the cylinders, the charges on the inside will unite with those on the balls and neutralize one another, resulting in an addition to the positive charge on *D* and the negative on *E*. When *A* and *B* are removed from their respective cylinders, they are entirely discharged, and can again be placed in the

position indicated in Fig. 20; but as they are now subjected to a stronger induction, the bound and free charges will be greater, and they will be able to deliver greater charges to the cylinders. It can easily be seen that, by repeating these manipulations, the potential difference between D and E will con-

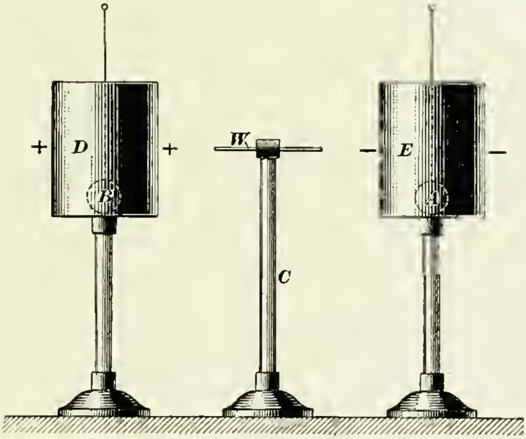

Fig. 21.

stantly increase, and will after a while be very high; it may indeed be said to increase at the rate of the *compound-interest law.*

THOMSON'S REPLENISHER.

49. Construction and Action.—An apparatus built on these principles, but continuous in its action, and called a *replenisher*, was devised by Sir William Thomson (in 1867), and is illustrated in Figs. 22 and 23 in diagrammatic views. In order to better compare them, the parts corresponding with those of Figs. 20 and 21 have been marked with the same letters. D and E are stationary brass conductors, A and B brass carriers fastened to the ends of an arm F, made of ebonite and revolving with the spindle G in the direction indicated by the arrow. In place of the wire W in Fig. 20, we have here a wire W with two springs W', and, instead of touching the cylinders with the balls, as represented in Fig. 21, there are two

contact-springs S, S projecting through an aperture in the inductors, and connected electrically with them. It is supposed that D has a small positive charge, and E a small negative one. Fig. 22 represents the position at the moment when A and B are under the inductive influence of the conductors D and E; at the same time they are connected with each other by means of the springs W' and wire W. Negative electricity is bound on the exterior side of A, while a positive charge is made free; on B a positive charge is bound, while a negative charge is free. The free charges will unite through the wire W and neutralize each other, and, when F continues its rotation, there will be a free negative charge on A and a free positive charge on B. Fig. 23

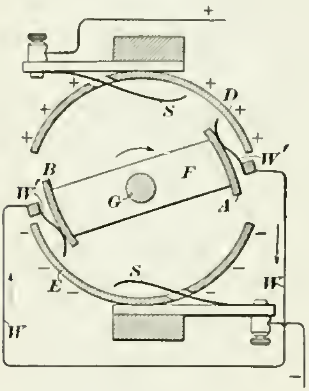

Fig. 22.

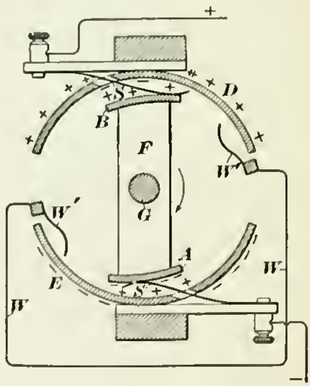

Fig. 23.

represents the position in which the carriers make contact with the springs S. The negative charge on A attracts positive electricity to the inside of E, and repels a negative charge to the outside; the spring S establishes communication between the negative charge on A and the positive charge on E, and a neutralization takes place, leaving on E an increased negative charge. A similar action takes place on D, leaving it more strongly charged positively. The carriers A and B are now discharged, and, when they again reach the springs W', they will be subject to a stronger induction than before, and will thus continue adding to the charges on the inductors. If the action of this "replenisher" is thoroughly understood, it should

not be difficult to understand the action of the modern induction-machine, which ordinarily, without due study, is not quite easy to grasp.

The most important types of this class are the *Wimshurst* and *Holtz* machines, so named after their inventors. In this country the latter is mostly used, while a small Wimshurst machine, placed in combination with the Holtz machine, serves the purpose of giving the latter its initial charge.

THE TOEPLER-HOLTZ MACHINE.

50. Construction.—The machine originally invented by *Holtz* was improved by *Toepler*, and constitutes in this form the *Toepler-Holtz machine*, now extensively used. Other variations of the Holtz machine are easily understood, when the principle of this type is fully grasped, and it will therefore be sufficient to limit our explanations to this one type.

The Toepler-Holtz machine may be considered as a Thomson replenisher, the difference being that the carriers are placed on revolving glass plates instead of forming parts of a cylindrical surface, and that the number of carriers is increased. It may simplify matters by first explaining the action of the Holtz machine in the form of a replenisher, and then give an example of its practical form.

51. Diagrammatic View of Holtz Machine.—In Fig. 24 we find a diagrammatic view of such a replenisher, varied so as to correspond in action to that of a Toepler-Holtz machine. D and E are *field-plates* made of tin-foil attached to the outside of the glass cylinder A, which is stationary. B is another cylinder, which is revolving in the direction of the arrow x, and is provided with *carriers* a, b, c, etc., also made of tin-foil. To obviate the necessity of the brushes w_1 and w_2 touching the carriers, small metallic buttons n are attached to the latter, which serve the purpose of transmitting the charges from the carriers to the brushes. We will now suppose that the field-plate D possesses a small positive charge, and that the carrier a is under its inductive influence. A negative charge will then be

attracted in the latter towards the side facing D, and will be bound, while a positive charge will be repelled and flow into the *neutralizing brush* w_1, which connects with the other brush w_2 possessing a negative charge. The charges will neutralize each other, leaving a in possession of a bound negative charge. As soon as the carrier a passes away from D and is no longer under its inductive influence, the bound negative charge will be free, and will, when the carrier passes under the brush s, be collected by the latter and sent into the field-plate E, which is then negatively electrified. This field-plate will now, when the carrier a occupies the position of carrier d, induce a positive charge on the side facing it, and repel a negative charge towards the side next to the comb C_1. The same action will then take place that was described in Art. **48**; that is, positively-charged air will be driven from the comb C_1, neutralizing part of the free negative charge on the carrier. The conductor P_1 is thus given a negative charge. When the carrier now proceeds

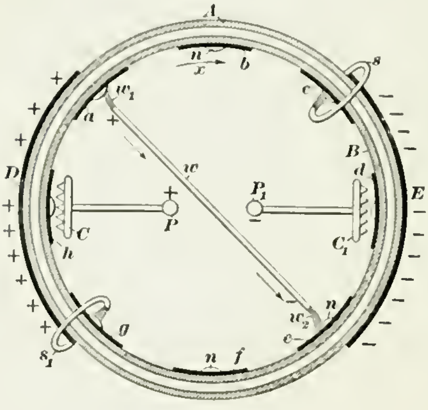

Fig. 24.

to the position e, the neutralizing brush w_2 will remove whatever negative charge is left, and combine it with the positive charge taken up by brush w_1, so that, when the carrier proceeds to occupy the position f, it is in possession of a free positive charge. This charge will now be of a higher potential than that on the field-plate D, and, when communication is established between the two charges by means of the brush s_1, an equalization will take place, and both will be of the same potential, thus increasing the potential of D.

52. The Carriers.—The carrier, when moving into position h, will induce a negative charge on the comb C, causing

negatively-charged air to be driven against the carrier, and thus making the other end P the positive terminal of the machine. Whatever positive charge is left on the carrier will, when it reaches the position a, be neutralized by the negative charge on the carrier e, so that carrier a is again in possession of a negative charge, but stronger now than the charge that resided on the carrier when we began our cycle.

We see, then, that the carriers, when leaving the position a, have free negative charges, which they deliver to the field-plate E, while the carriers after leaving this field-plate are ready to deliver positive charges to the field-plate D. The potential of these two plates will be increased until the leakage between them keeps up with the supply, when a further increase is prevented.

At the same time that the potential of the field-plates has been raised, that of the free charges on the carriers has also been increased, and thus induced charges of progressively higher potential will be set free at the terminals of the conductors P and P_1.

53. The Field-Plates.—There will now be little difficulty in understanding the action of the Toepler-Holtz machine, as illustrated by Fig. 25. For the sake of making comparison easier, the same letters have been used as in Fig. 24, on those parts which have the same functions to perform. Thus, A is a stationary glass plate, shown separately in Fig. 25 (c), on the back of which the field-plates D and E are cemented. Each field-plate consists of a piece of tin-foil, the surface of which is protected by a layer of varnished paper. The movable plate with the carriers is B, as before, and the carriers are a, b, c, d, e, f. As the latter are of tin-foil, and therefore liable to injury by the rubbing of the tinsel brushes S and S_1, they are provided with small brass buttons a_1, b_1, etc., shown in Fig. 25 (b), which alone make contact with the brushes, and thus shield the carriers.

Fig. 25 (a) shows the plates in position, the revolving plate B being in front. If we again suppose the field-plate D to have a small positive charge, the carrier a will have a *bound* negative and a *free* positive charge. The latter will be removed by the

neutralizing brush w_1, and the carrier will therefore reach the position b with a *free* negative charge, which will be imparted to the field-plate E by the brush S, as already shown. It is

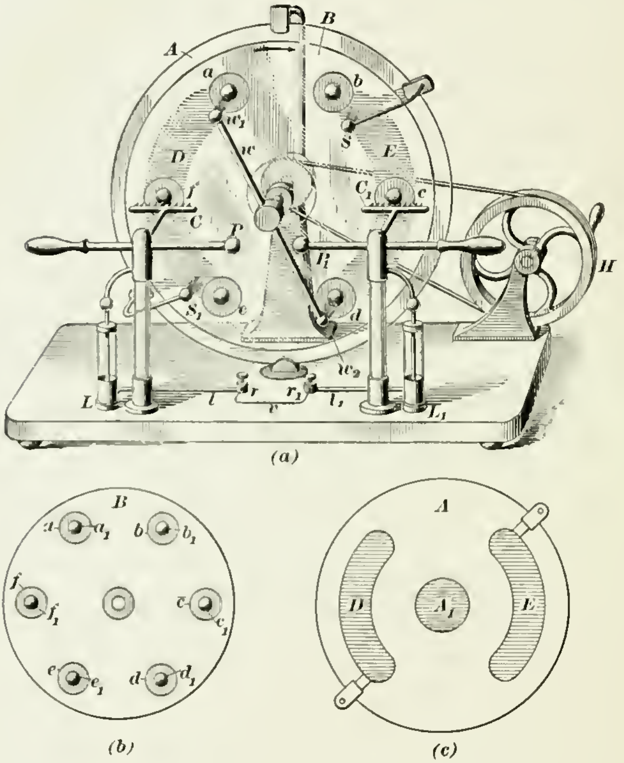

Fig. 25.

unnecessary to describe the operation any further, as it is exactly the same as that of Fig. 24.

54. It is seen that the plate A and the collectors are supported by glass columns, to insure perfect insulation. The discharge-rods P and P_1 can slide in their supports, thereby making it possible to change the length of the air-gap between the two rods. These discharge-rods are also electrically connected with the Leyden jars L, L_1, which will accumulate the

electric charges of the rods, reducing the number of sparks, but increasing their strength. The outer coatings of the jars are electrically connected by means of strips l, l_1, binding-screws r, r_1, and wire v. The charges passing between terminals r, r_1 can also be sent through various appliances, or through the human body.

The plate B is set in rotation by means of the pulley H, which engages a smaller pulley on the shaft of B. When starting the machine, the brushes should be set so as to make good contact with the revolving carriers, and the discharge-rods should be drawn widely apart. A few turns will then suffice to charge the machine, and, if the discharge-rods P, P_1 are now brought closer together, sparks will pass behind them.

It should here be remembered that positive charges are not sent into the comb C from the plate and transferred from there to the rod P, but that negative charges are constantly withdrawn from the comb and neutralized by the carriers, leaving a positive charge on the end of the discharge-rod at P

When P and P_1 are near enough to permit sparks to pass between them, the positive charge on P will be neutralized, but a negative charge will immediately be withdrawn from the comb C, leaving a positive charge again at P, as before. The reverse takes place at the positive comb C_1; here positive charges are constantly sent towards the plate, thus leaving negative charges on the discharge-rod P_1.

55. Though the carriers perform most of the work of carrying the + and — charges from brush to brush and to the combs, it must not be supposed that the plate B is neutral. On the contrary, this plate could work even without the carriers, but it would be difficult to put the machine in operation. After the machine is once in action, this glass plate is also in possession of a strong positive and negative charge, placed diametrically opposite each other, which, as their potentials increase, tend to leak across the plate and unite with each other. This action of the plate, therefore, limits the possible potential that the carriers otherwise might have attained.

In some types of Holtz machines the carriers have been

omitted, and the neutralizing brushes w_1, w_2 replaced by neutralizing combs. To facilitate the starting of the machine, the field-plates *D*, *E* are connected with a small Wimshurst machine, which gives them a high initial charge, after which the machine at once is in full action, and able to maintain the charges.

THE WIMSHURST MACHINE.

56. Principles of Construction.—Another type of induction-machine is the Wimshurst machine, which has been very extensively used in Europe. Though in some respects it is superior to the Holtz machine, it has not gained ground in this country, so far as its use in therapeutics is concerned; it seems that the strength of current it is able to furnish is smaller than that of a well-made Holtz machine, and that it is, as regards mechanical construction, less enduring than the other. It has this advantage over the Holtz machine, that it is self-starting, and is therefore used very extensively in combination with the latter machine, it being always ready to furnish the necessary initial charge.

57. Fig. 26 will explain the main principle of this machine. *A* and *B* are glass cylinders provided with carriers numbered

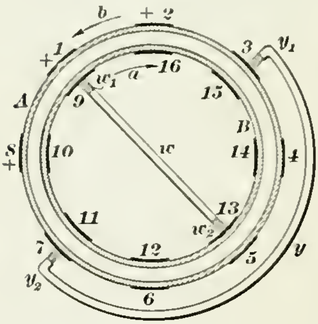

Fig. 26.

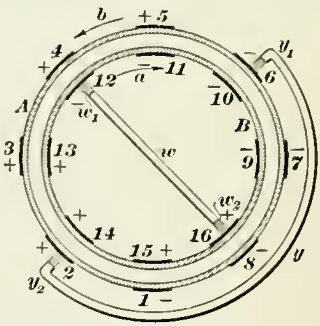

Fig. 27.

1, *2* . . *8*, and *9*, *10* . . . . *16*; w_1, w_2 are the neutralizing brushes for the interior, and y_1, y_2 the neutralizing brushes for the exterior cylinder. We will first suppose that the exterior cylinder is stationary, and the interior revolving in the direction

of the arrow *a*. Let it further be supposed that the carriers *8*, *1*, and *2* have an initial positive charge. The carrier *9* will then be subjected to an inductive influence due to these three carriers, and it will therefore assume a bound negative charge, and the free positive charge will be neutralized by the brush w_1.

When the carrier *9* changes its position to that of carrier *15*, it will be removed from the inductive influence of the positively-charged carriers, and will have a free negative charge of a slightly higher potential than that held by *8*, *1*, or *2*. When, then, carrier *9* occupies the position of carrier *15*, it is inducing a positive, bound charge on carrier *3*, and a free, negative charge is neutralized through the brush y_1.

If we now set cylinder *A* in rotation in the direction of the arrow *b*, carrier *3* will subsequently reach the position of carrier *1*, where its positive charge is free and of a higher potential than that possessed by carrier *1*. The fact that each carrier on these cylinders is exposed to the inductive influence not only of the carrier placed opposite, but also to that of the adjoining carriers, constitutes the main feature of the Wimshurst machine. This explanation of its action appears as acceptable as any, and is justified by the fact that the Wimshurst machine will work to better advantage with, say, sixteen sectors per plate than with a smaller number. Ordinarily, these carriers are much closer together than shown in the diagram, and their combined action is therefore much stronger. If each carrier were able to influence only the carrier confronting it, no increase in potential could be gained, and the charges would soon decrease ; but, as it is, the charge induced on each carrier is appreciably stronger, if it is under the joint inductive influence of more than one carrier instead of one only.

58. Fig. 27 shows the condition of the machine after each of the cylinders has made three-eighths of a revolution. We find then that one-half of each cylinder is positively, the other half negatively, charged ; in either case the neutralizing rod constitutes the dividing line.

59. Fig. 28 shows a similar machine, in which all the brushes have been replaced by combs, and the carriers removed,

leaving bare glass cylinders. For collecting the charges, the combs C and C_1 have been added. The diagram plainly shows the condition of the glass cylinders, and how the free charges are neutralized by the combs C, C_1, thus leaving the conductors P and P_1, respectively, positively and negatively charged.

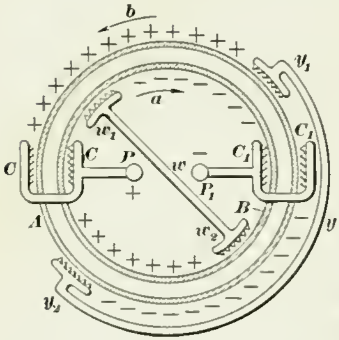

FIG. 28.

60. Fig. 29 gives a perspective view of a Wimshurst machine. The glass cylinders used in the previous description are here replaced by two glass plates A and B, on the outside of which are cemented a number of sector-shaped plates, serving as carriers and inductors. The function of these sectors is changed twice during each revolution of the plates, from a carrier to an inductor, the carriers on one plate serving as the inductors for the carriers on the other plate. These glass plates are coated with shellac, and are attached to the ends of two hollow bosses of wood or ebonite provided with pulleys. Each plate revolves independently on a fixed steel spindle S, motion being imparted to the pulleys by means of cords passing over corresponding pulleys in the lower part of the machine. The plates are $\frac{1}{8}$ inch apart, and are revolved in opposite directions by crossing one of the cords. The curved conductors w, y, with fine-wire brushes at their ends, are the neutralizing rods, and are placed at an angle of about 90° with each other. Two metallic conductors F and G have

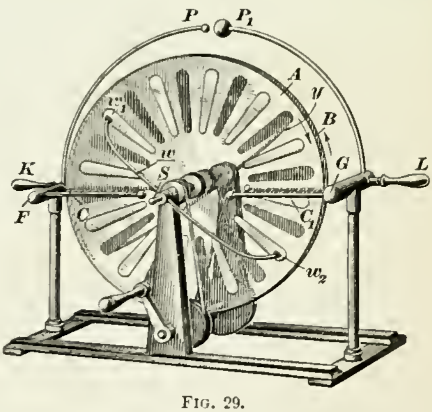

FIG. 29.

each two collecting-combs C and C_1, one for each plate. These conductors are, as usual, insulated from the ground by means of glass columns, and carry two discharge-rods P, P_1, terminating in balls; the distance between these can be changed by moving the handles K, L either up or down.

A Wimshurst machine will be able to maintain charges of a higher potential if the carriers are removed, but it will not start quite as readily. The use of the carriers has the disadvantage that it changes a large part of the revolving plate into a conductor, and thus facilitates the leakage between charges of opposite potentials.

MODES OF DISCHARGE.

61. It has been stated previously that there were not different classes of electricity—that, no matter by what means a difference of potential was created, the same kind of electricity would flow. Its elementary nature would always be the same, but it might be made to show different characteristics in the manner of flowing by variations in the apparatus. For instance, it might be a *continuous*, or *pulsating*, or an *alternating* current. These three variations refer mainly to the character of its flow through a conductor, but for a *high* electromotive force there are also other means open for a discharge. It may take place in any of the following three forms: (1) by convection; (2) by disruption; (3) by conduction.

CONVECTIVE DISCHARGE.

62. We have already seen how a *convective* discharge took place in the static electric machine, when the collecting-combs discharged their induced charge by means of electrified air, repelled towards the revolving plates. A pointed metallic rod connected with the prime conductor of a machine will discharge itself in this manner if the electromotive force exceeds 20,000 volts. This motion of the air is called an electric *breeze*, and is utilized as such in electrotherapeutics.

DISRUPTIVE DISCHARGE.

63. The second form of discharge, the *disruptive*, has been observed when the electrophorus was considered; it was noticed that, after the disk had been removed from the cake and then approached by one of the hands, it would discharge itself by means of a spark. The same will take place if the discharge-rods of a static machine are brought near enough together.

It has been found experimentally that it takes a potential difference of about 8,000 volts to send a spark between two metal balls separated by an air-gap of one-tenth of an inch, so that it would take about 80,000 volts to send a spark through a gap of 1 inch. If one of the conductors is pointed and the other provided with a plate, the necessary voltage for a 1-inch gap will be decreased to about 23,400 volts. This applies to a distance of up to 3 inches; beyond this the voltage per inch decreases.

The distance between the discharge balls of a static induction-machine determines the maximum potential difference that can be developed between them; if, therefore, the balls were separated a distance of one-half an inch and the machine turned just fast enough to send a spark across, we would know that the potential would be about 40,000 volts.

These relations between voltage and sparking distance do not hold true when we have to do with an alternating current, such as derived from an induction-coil. It is not the *virtual* voltage that is here the deciding factor, but the *maximum* voltage. To send a spark across an air-gap of 1 inch with an ordinary induction-coil will therefore require less voltage, or from 40,000 to 50,000 volts.

CONDUCTIVE DISCHARGE.

64. We have already considered this form of discharge when it took place under moderate pressures; but when it comes to the high pressures produced by a "static induction" machine, the conditions are no longer the same. This should not be surprising, as it has been shown that an electric current behaves as if in possession of *inertia*. When, therefore, a current

of electricity is sent through a conductor under such enormous pressure as a static machine is able to produce, it would be natural to suppose that the current, after once being started, would tend to continue its motion, creating a reverse pressure.

A swinging pendulum works under somewhat similar conditions. On pushing it to one side and releasing it, it will not stop in a middle position, but will pass beyond this to the other side. This will continue until the energy imparted to the pendulum has been wasted in overcoming frictional resistance. With no resistance to overcome, the oscillation would continue forever.

65. It must not be understood from these remarks that discharges taking place under high pressure are *always* oscillatory. This is not the case; certain conditions have to be fulfilled before a discharge of this nature will occur. There has to be a certain relation between the resistance of the circuit, its self-induction, and its capacity; otherwise, the discharge will take place as ordinarily, that is, by a gradual equalization of the positive and negative potential.

To return to the case of the swinging pendulum; we can, for instance, well understand that, if a large fan be fastened to the pendulum, the air resistance may be so great that the pendulum would slowly swing to its middle position and stop there. In the same manner, if the conductor of a static induction-machine is connected by a slightly-damp linen thread, the discharge will pass through it more gently, and oscillations will not be set up.

This slow conductive discharge may be compared with a light body falling slowly towards the earth, and settling down gently. The disruptive discharge, on the other hand, is more like the action of a steel ball falling from a certain height on to a metal plate. It will rebound again and again, and little by little come to rest.

66. To better understand the relation between resistance, self-induction, and capacity, we may again use the hydraulic analogy of a condenser, as was used in explaining the action of the condenser in connection with an induction-coil. Let A and

B, Fig. 30, be two tanks filled with water, and communicating with the cylinder c by means of pipes a and b. The piston d is able to move either to the left or to the right, being held in a middle position by springs e and f.

If now we imagine the water-level of tank A suddenly raised by pushing the piston d to the left and then releasing it, there will be a difference of level between the water in the two tanks. Water will then flow from tank A, so as to reestablish the former level, and the water-columns in pipes a and b will be set in motion. After the piston has reached its middle position again, the water, by reason of its inertia, will tend to keep up its motion, and, therefore, to move the piston to the right. As soon as the energy of the moving water has been used up in extending and compressing the springs e and f, motion will cease, and the springs will now try to assume their normal form by pushing the piston to the left. To do so, the water-columns in pipes a and b are set in motion, and the water-level in tank B is lowered, while that in A is raised. Again, the inertia of both water-columns tends to maintain the motion, and the result will be that now the piston is moved too far to the left.

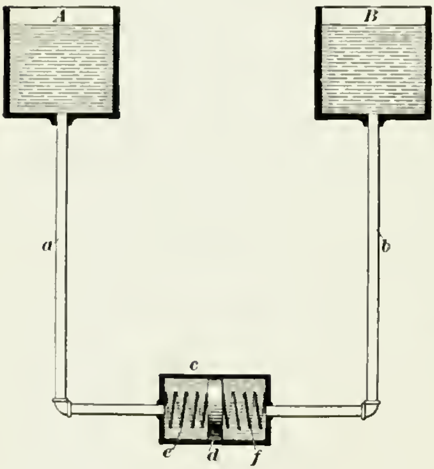

FIG. 30.

If the water, the pipes, and the moving parts were devoid of all friction, the to-and-fro motion would continue indefinitely, without any diminution in the amplitude of the oscillations. But it is easily seen that the friction of the water and the piston will soon consume the energy originally imparted to the piston, and the oscillations of the latter will therefore gradually decrease in amplitude, and at last cease altogether.

67. Let us now see how the character of these oscillations is influenced by the dimensions and nature of the circuit. It is clear that the longer or the wider the cylinder *c* is, the more water can flow into it before the piston has strained the springs to their limit, the more *capacity* the cylinder therefore has, and the longer it will take before the piston will stop and move in the opposite direction; there will therefore be fewer oscillations per second.

If the inside of the pipes is rough, thus offering much *resistance* to the flow of the water, more energy will be consumed in friction and less will be left for moving the piston against the resistance of the springs. It is seen that, if this resistance is made large enough—for instance, by fitting the interior of the tubes with coke—the return of the piston, after having been moved to the left, might be so slow and consume so much energy that it would not only be unable to oscillate, but might even be unable to reach its middle position again.

It will also be seen that the length or diameter of the pipes will have some influence, as these dimensions determine the volume of water contained in the pipes. A given force will require a longer time to set a large volume of water in motion than a small one; and a large volume, after once being set in motion, will continue this motion against an opposing force for a longer time than a smaller volume of water is able to. In both instances, the *inertia* of the water tends to oppose both the beginning and the cessation of motion.

68. The conclusions we arrive at are, then, as follows: that, in order to have the piston perform oscillations, the resistance of the pipes has to be below a certain value, otherwise there will only be a gradual discharge in one direction. To have long and powerful oscillations, the volume of the water set in motion must be large, and also the capacity of the cylinder *c*. If, on the other hand, this capacity is small, it will take a small motion of the piston in either direction to bring the springs up to their maximum resistance; the oscillations will therefore be of short duration, and their frequency will increase as the capacity of the cylinder decreases. It will be seen from this that it is not

possible to have a large volume of water perform oscillations of great amplitude and high frequency, because a high frequency requires a *small* capacity of the cylinder, while, on the other hand, a great amplitude demands a *large* capacity.

69. The sudden discharge of an electric circuit is affected by conditions somewhat similar to those influencing the oscillations of the water-columns. The condenser effect of a circuit, or its *electrostatic capacity*, corresponds to the cylinder *c* with its piston and springs; the longer and weaker the springs are, the longer and slower the oscillations are, and this would correspond to a high electrostatic capacity. On the other hand, the shorter and thicker the springs are, the shorter and more rapid the oscillations will be.

The *resistance* of the circuit would correspond to the resistance that the fluid would meet with in passing through the pipes. If this resistance is too high, oscillations will not take place in either the hydraulic or the electric circuit.

The *self-induction*, or electromagnetic inertia, corresponds to the volume of water in the pipes; the greater this volume is, the slower, but at the same time more powerful, the oscillations will be. The same holds good in the electric circuit; the greater the self-induction, the more difficult it is to start a current, and, after it is started again, to stop it.

70. Examining more closely into the conditions required for an oscillating discharge, we observe that the production of rapid and at the same time powerful oscillations will meet with some difficulty. The reasons are the same as those which prevented powerful and rapid oscillations taking place in the hydraulic circuit. To have rapid electric oscillations, the electrostatic capacity and self-induction must be small. On the other hand, long and powerful oscillations require a current of great strength and a circuit with a *large* electrostatic capacity. But a strong current has a large amount of self-induction. We see, therefore, that rapid oscillations cannot be combined with a strong current, but must go hand in hand with a feeble one.

71. The conditions under which a sudden discharge takes place are usually such as to make the discharge an oscillating one. This is perhaps hard to realize; it seems that, when we discharge a Leyden jar, or let a spark pass between the prime conductors of a static induction-machine, we see just one spark and nothing more. But examinations by means of rotating mirrors and extremely delicate galvanometers have shown that a series of oscillating discharges pass back and forth.

The frequency of such oscillations may be as much as hundreds of millions per second. Ordinarily, these oscillations cease quickly, and number from 2 to 50 before equilibrium is established; the whole phenomenon will therefore occupy only a small portion of a second, and in too brief a time for the human eye to perceive any oscillations. A Leyden jar of the size ordinarily used will discharge itself by oscillations with a frequency of 15,000,000 cycles per second, each cycle consisting of one oscillation to and fro. Though ordinarily

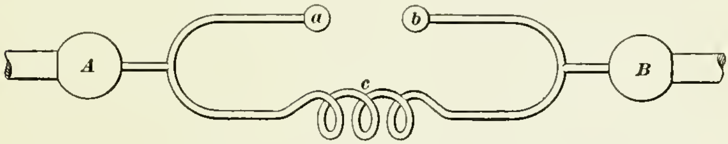

Fig. 31.

the total number of oscillations are few, it is possible by suitably adjusting the condensers to let a discharge consist of as much as 20,000 double alternations before all its energy is expended.

72. The resistance of a circuit is not the only factor that determines whether a discharge will take place through it or not. For instance, if, in Fig. 31, the prime conductors *A*, *B* of a static induction-machine are connected with each other by means of two conductors in parallel, in one of which there is a spark-gap *a b* and in the other a coil *c* of 3 or 4 turns, it is a question whether or not the discharge will pass through the coil *c*. If the pressure of the charge is high enough, the self-induction of the coil *c*, even with a few turns only, may be so

high as to make the resistance of the air-gap $a\ b$ relatively lower in comparison, so that the charge will take this path in preference.

STATIC INDUCED CURRENTS.

73. Oscillating discharges of the character previously described are used for various purposes in electrotherapeutics, either to cause the flow of so-called *static induced* currents or for the operation of the *Tesla* coil.

When used for static induced currents, an arrangement is made as shown in Fig. 32. A and B are again the prime conductors of a static machine, and a, b the discharge-rods. The internal coating of the Leyden jar c is connected with the conductor A, while the external coating is in metallic connection with the binding-post e; the jar d is similarly connected

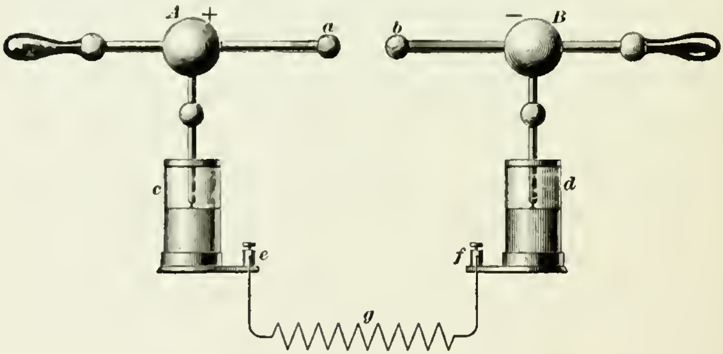

FIG. 32.

with the conductor B and binding-post f. The conductor g establishes electrical communication between the binding-posts. Though the circuit $e\,g\,f$ is entirely insulated from the static machine, it is possible to establish oscillating currents in this circuit in the following manner :

74. Let us suppose that small positive charges are constantly sent to the conductor A, and negative charges to the conductor B. By reason of the air-gap between a and b, these charges are not able to unite, but flow into the jars c and d

on the inner coatings, and induce charges of opposite polarity on the outer coatings. These charges continue to flow into the jars, where they remain as bound charges, held so by the charges induced on the outside coatings. For instance, if positive charges are flowing from A into the jar c, negative charges are induced on the outside coating, and in the same manner a positive charge is held on the outside of the jar d. Both of these outside charges are *bound*, and cannot therefore unite and neutralize each other through the conductor g.

This charging of the jars will continue until the difference of potential between the inside charges of the two jars has reached such a value that it is able to overcome the resistance of the air-gap $a\,b$, and bridge it by means of a spark. When this has taken place, the inside charges have neutralized each other, and the outside charges are now free and will unite through the wire g, when a current will flow from f to e. If, now, the human body constitutes part of the conductor g, it will also be traversed by these currents, and we have then an apparatus that has some similarity with an induction-coil, in so far as the circuit $e\,g\,f$, which may be called the *secondary* circuit, is insulated from the conductors A, B, in this case serving as a *primary* circuit. Here the similarity stops, and it may be added that the leading principle in this phenomenon is widely different from that utilized in the induction-coil, and that therefore the term *static induced currents* is rather misleading.

75. Under ordinary circumstances, this discharge between the knobs a and b will be oscillating, and the following will take place: A positive charge will flow from a to b, tending to neutralize the negative charge on the latter, but the self-induction of the circuit causes an excess of current to rush towards B, and charges the latter positively. As soon as the current has come to rest it will again seek to equalize the pressure by rushing back to A. The self-induction will again cause an excess of current to go to A, and a reversal will take place; these reversals will continue until balance has been restored.

At the same time as these oscillations have been going on between the knobs a and b, the inside charges of the Leyden

jars have, of course, suffered the same changes in potential, and therefore compelled the outside coatings to change simultaneously, with the result that an oscillating current has also been flowing between the posts *e* and *f*.

The frequency of these oscillations will, as previously explained, depend on the capacity of the jars and the rest of the circuit, and also on its self-induction; ordinarily, this frequency is from 200,000 to 300,000 cycles per second. The resistance of the circuit *e f g* and the air-gap *a b* will determine the number of oscillations that the discharge will perform before its energy has been spent.

Essential Apparatus.

ESSENTIAL APPARATUS.

APPARATUS USED FOR CONTROLLING AND MEASURING.

CELL-SELECTORS AND SWITCHBOARDS.

1. Single-Handed Selectors.—When a voltaic battery consists of a large number of cells, it is very likely that the whole battery is used only on rare occasions and that more frequently merely a small part of it is put in action. In such instances it would not only be inconvenient to constantly have to disconnect and reconnect the various cells, but it would also give opportunity for making wrong as well as poor connections. It is therefore preferable to have the cells connected up once and for all, and to use other means for selecting the required number of cells, or for rearranging them in a manner suitable for the purpose for which they, at the time being, are intended.

If the cells are constantly used in series, and it is only required to include a greater or smaller number in this series, then devices called *single-handed* and *double-handed selectors* are used. These are illustrated by means of Figs. 1 and 2. If the battery contains a small number of cells, the single-handed selector shown in Fig. 1 may answer the requirements. For a greater number of cells, the double-handed selector, illustrated by means of Fig. 2, has certain advantages, not obtainable from the other.

Fig. 1 is a diagrammatical view of the selector and battery connections. The letters E_1, E_2, etc. indicate the separate cells, while z and e stand, respectively, for the negative and positive

poles of the same. The latter pole in each cell is connected with the negative pole of the preceding cell by means of wires c_1, except the positive pole of the first and the negative pole of the last cell, which communicate directly, by means of wires c_2 and c_3, with their respective studs d_0 and d_6. The wires c connect the other studs to the cross-connections c_1 already mentioned. A is a plate of insulating material, as ebonite, slate, or hard wood well varnished, in which the studs or buttons d_0, d_1, etc. are inserted, and over which the lever, or hand B, is intended to move and establish contact. The hand B is pivoted on the

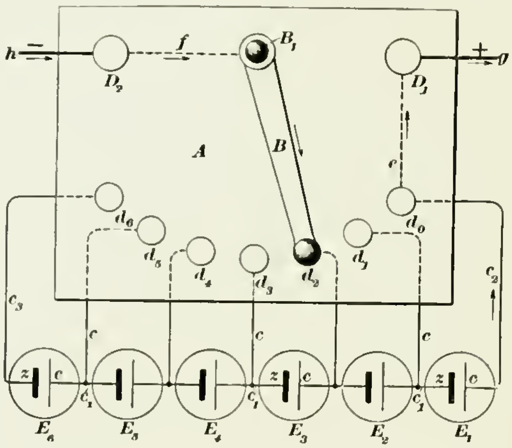

FIG. 1.

stud B_1, which latter connects with the negative terminal D_2 through the wire f. The other terminal D_1 is connected to the stud d_0 by means of the wire e. All these connections are, as indicated by the dotted lines, under the plate A and therefore out of the way, except the wires g and h, which connect the selector with the device upon which the electric current is intended to act.

In the present position of the hand, the first two cells E_1 and E_2 are placed in action, while the remaining cells are out of circuit and inactive. If the hand B is placed on the stud d_1, the cell E_1 alone will be in action. It is thus seen that, by moving the hand to the left, more and more cells will be placed

in action, until, when the stud d_6 is reached, all the cells are included in the circuit. The drawback inherent in this selector is the necessity of using some of the cells more than others. For instance, E_1 will be included in any combination, and will therefore be sooner exhausted than the rest; while E_6 will last the longest because less frequently used.

2. Double-Handed Selectors.—To obviate these drawbacks, the double-handed selector, illustrated in Fig. 2, has been

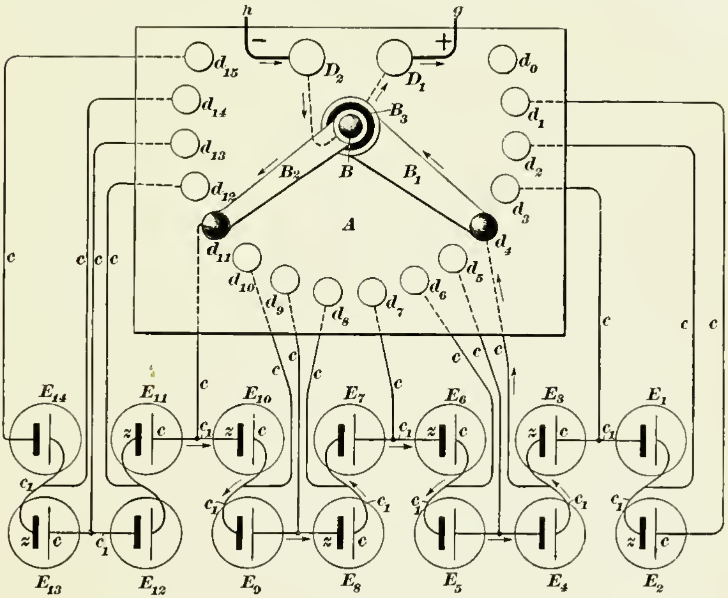

FIG. 2.

designed. Here it is possible, if less than the whole number of cells is needed, to select any number of cells in any part of the series, and let these alone be acting, independently of the cells preceding or following in the series. This is accomplished by the introduction of an additional hand B_2. The interconnection of the cells, and their connections with their respective studs, are exactly the same as in the preceding figure. The new feature is found in the hands, one of which, B_1, connects with the

positive terminal D_1, while the other, B_2, connects with the negative terminal D_2. The two hands are insulated from each other by the insulated bushing B_3; B_2 and B_3 revolve around the stationary stud B. There is an additional stud d_0 which has no connection with the cells; whenever the hand B_1 makes contact with this stud, the battery is on open circuit, and no current will flow through the wires g and h. It is seen that, if one cell only is required, it is just as easy to use the last as the first cell; in fact, any single cell can be selected. For instance, placing the hands on d_{14} and d_{15}, the cell E_{14} alone is in operation; while on making contact with d_7 and d_8, only the cell E_7 is in circuit. In either of the figures the arrows indicate the direction of the current from the negative to the positive terminals.

3. Selectors as Current-Regulators.—It is clear that these selectors will also serve as current-regulators: in Fig. 1, by placing the hand B on the stud d_1 and gradually moving it from stud to stud, and in Fig. 2, by letting the hand B_1 remain stationary on d_1 and moving B_2 over the studs towards the left. In either case the E. M. F. will be increased, and, if the external resistance remains constant, also the current-strength. If the addition of one cell at a time should make the increase in E. M. F. too great, a rheostat may be used in conjunction with the selector, which would enable the latter to increase the pressure with less abruptness.

4. Precautions to be Observed.—Care must be taken not to leave a hand between two studs in such a manner as to make contact with both, as otherwise the cell that is inserted between these studs will be short-circuited and perhaps suffer permanent injury. If, for instance, the hand B in Fig. 1 should be left between the studs d_4 and d_5, then the cell E_5 would be short-circuited, because the current could pass from d_4 through B and d_5 back to the cell.

5. It is not always that *every* cell is connected with a stud; sometimes it is only every second or third cell. In that instance the pressure is increased by that of two or three cells at a time. This is done when the number of cells is very great, in order to avoid too many connections.

SWITCHBOARDS.

6. The Mercury Switchboard.—Evidently these selectors are unable to connect the cells in any other way but in series, unless the cells are divided into parallel groups and these again connected in series parallel. But even then the combinations are limited in variety, and when other connections are

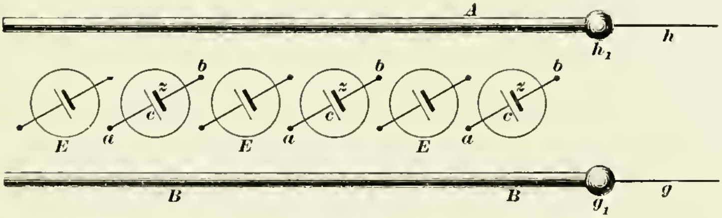

FIG. 3.

needed, as, for example, uniting all the cells in parallel, other means must be found for accomplishing these results.

For this purpose a *mercury switchboard* is very useful, as it enables various combinations of cells to be quickly made without altering the individual connections of the cells. Before describing a switchboard of this class it will be well to illustrate its principles by means of some analogous device, as shown in Fig. 3. Here we have a row of cells, entirely independent of one another and without any external connections. The posi-

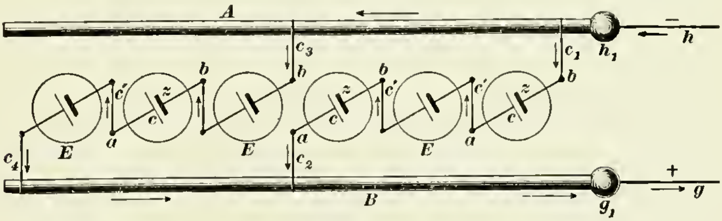

FIG. 4.

tive and negative poles of the cells are designated by the letters c and z, respectively; short pieces of wire join these poles to external binding-posts a and b. At either side of the cells are metallic rods A, B provided with terminals h_1, g_1 and conducting wires h, g. By means of additional pieces of copper wires, the cells can now be connected both with one another and with

the metal rods, which latter in reality are extensions of the terminals g_1 and h_1. Fig. 4 shows one mode of combining the cells. After the first 3 cells on the right have been joined in series by means of the connectors c', their negative terminal b is connected through the wire c_1 to the negative rod A, and their positive terminal a through the wire c_2 to the positive rod B. The external circuit $g h$ will then have the E. M. F. of 3 cells and the current of 1 cell. By joining the remaining 3 cells in the same manner and connecting them to the rods by wires c_3 and c_4, we have the same E. M. F. as before, but the current-strength is now that of 2 cells. If the wires c_2 and c_3 be removed, and the terminals a and b, at that point, connected as the rest of the cells, then all would be connected in series, and the circuit would receive a current with a pressure corresponding

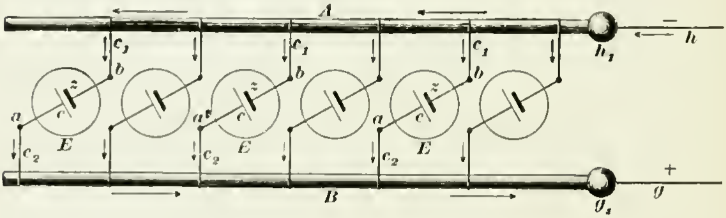

FIG. 5.

to that of 6 cells, but with a current-strength equal to that of 1 cell only.

Again, if the connectors c' are removed and each cell connected to the rods A and B, we have the combination shown in Fig. 5. All the cells are now in parallel; the total E. M. F. is that of 1 cell only, but the current-strength has increased to that of 6 cells.

7. As far as varying the combinations of the cells, this apparatus is just as efficient as a mercury switchboard, but it is not practical; it takes too much time to make the connections. In the mercury switchboard, as shown in Fig. 6, no connections are made by means of binding-screws, etc., but simply by the use of staples or bridge-pieces c' of a form as shown at (a) Fig. 6.

The switchboard consists mainly of a plate T, made of some insulating material, as slate, ebonite, or varnished wood, in

which cup-like depressions a and b are formed, replacing the binding-posts a and b in the previous figures. The rods A and B, Fig. 3, are here substituted by troughs A and B. The latter as well as the cups are filled with mercury. Small hooks e made of stout copper wire, with one leg longer than the other, have their long legs inserted through corresponding holes in the table, while the short legs dip in the mercury of the cups a and b. To those ends of the hooks which are projecting through the table, the poles of the various cells E_1, E_2, etc. are connected by means of the wires d, and these poles are again designated by letters c and z. The legs of the terminals

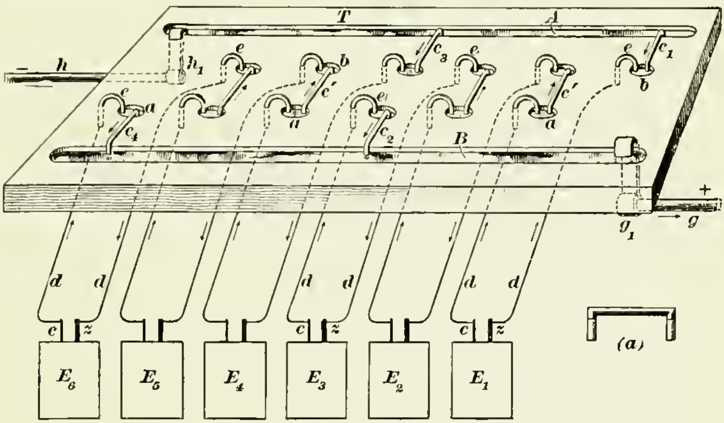

FIG. 6.

g_1 and h_1 are projecting through the plate T, and their ends bent over so as to dip into the mercury troughs. Corresponding parts of Figs. 4 and 6 are marked with the same letters.

It is now clear that, as all the cups b are connected with the negative and the cups a with the positive poles of the cells, the cups b must all be of a positive and the cups a of a negative potential. All that is now necessary is to connect the various cups and troughs by means of the bridge-pieces c', when a current of the desired E. M. F. and strength will be sent through the wires g and h.

The cups have been arranged so as to prevent a short circuit

of the cells. This has been attained by making the distance between the cups a and b, belonging to one cell, say E_1, greater than those between either of these cups and cups of adjoining cells. The bridge-piece c' is therefore long enough to join cup b of cell E_2 to cup a of cell E_1, but will be unable to bridge over the distance between the cups a and b belonging to cell E_1, and, therefore, also unable to short-circuit the latter.

Fig. 6 represents the same combination of cells as shown in Fig. 4. It is seen that the cells E_1, E_2, and E_3 are placed in

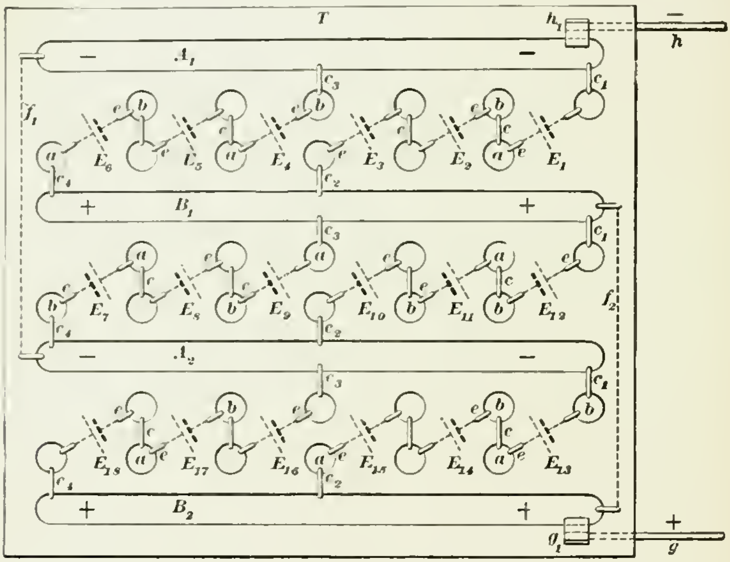

FIG. 7

series by means of two bridge-pieces, and that afterwards this group is connected to the trough A through the piece c_1, and to trough B by piece c_2. The mercury in either of these troughs transmits the current to their respective terminals h_1 and g_1. Another group of cells is formed and connected in the same manner and with the same results as in Fig. 4.

8. If a larger number of cells is required, it would be inconvenient to extend these into one long row, and in such instances they may be arranged in a manner similar to that

illustrated in Fig. 7. The latter is mainly an extension of Fig. 6, with some additional connections. The dotted lines which are seen between the cups *a* and *b* indicate the position of the cells and their connections with the hooks *e*. The first cell is placed in the upper row at the right, and the connections must proceed from there to the left, then down to the row below, where the order of progression is from left to right. At the end of the second row we proceed again to the third row, beginning at the right and reaching the last cell at the

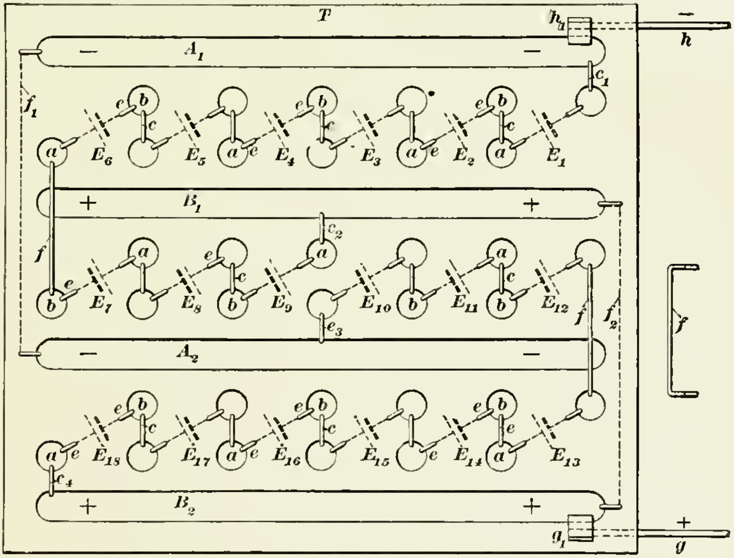

Fig. 8.

extreme left. The troughs A_1 and A_2 are joined by means of the wire f_1, and the troughs B_1 and B_2 by the wire f_2. It is clear that this table may be enlarged in either direction to suit the required number of cells.

In Fig. 7 we have the cells arranged in rows of three in series and six in parallel, after the manner shown in Fig. 6. The result is that the total E. M. F. will be that of 3 cells, while the current-strength will be that of 6 cells.

Fig. 8 shows the particular case where the cells are placed nine in series and two in parallel. After the cells in the first row

have been arranged in series, they require a connection with the row below; for this purpose the cell E_6 is joined to the cell E_7 by an additional bridge-piece f, as shown more fully in the separate figure, and then three more cells are added, to make up the 9 cells in series. At this place the piece c_2 connects them with the positive trough B_1, and another piece c_3 connects the other series of 9 cells with the negative trough A_2. The connections are now carried out, as previously shown, until the cell E_{12} is reached, when again an additional piece f is required to connect it with the cell E_{13} of the following row; then the connections proceed as before and are finished by joining the last cell E_{18} to the positive trough B_2.

It will scarcely need any additional explanation to show how other groups may be formed, or how to place all the cells in parallel or series.

AMMETERS, VOLTMETERS, AND RHEOSTATS.

AMMETERS AND VOLTMETERS.

9. Galvanometers and Ammeters.—If the electric current is to be used with any exactness, instruments are needed that will measure its strength and pressure. In its application to medical treatment this is particularly so, as the various purposes for which it is required demand various current-strengths. In some instances an overdose may not only be annoying but also dangerous, or may cause permanent injury.

When we speak of measuring the strength or pressure of an electric current it must not be understood to mean that it is measured in the same manner as a gasometer measures the quantity of gas flowing through it, or as the pressure of the gas by means of a gage, giving the pounds pressure per square inch. The strength of an electric current is measured more nearly in the same manner as an anemometer measures the speed of the wind. The former does not count the cubic feet of air passing it per second, but is simply set in rotation by the air-current. By otherwise finding the relation between the number of revolutions per second, caused by a certain speed of

this air-current, the speed of the latter can be read off directly from a scale.

So with electricity. We know that a coulomb per second constitutes an ampere, and it might therefore be supposed that measuring the number of coulombs would answer the purpose; but instruments of this character would not be practical for the present purpose. Neither would instruments based on the property of the current of depositing a certain amount of metal per coulomb of electricity.

In commercial measuring instruments, other properties of the electric current are found more convenient for use. Thus, modern instruments are based almost exclusively on the phenomena that two active conductors, or a magnet and a conductor, exert a certain mutual influence on each other; or, that an electric conductor will heat and expand in proportion to the number of amperes it transmits, and be able by means of the resulting elongation to operate a suitably arranged indicator.

10. The D'Arsonval Galvanometer.—Small currents were formerly mostly measured by means of the *galvanometer*; but lately such accurate and reliable portable measuring instruments have been made that these measurements may be carried out with as great a degree of precision and with much greater facility than with the various galvanometers. The latter instruments will, therefore, not be described, with one exception, the *D'Arsonval galvanometer*. Some of the best modern measuring instruments are formulated on the principles of this galvanometer, and it may therefore simplify matters by first describing it. It is illustrated by means of Fig. 9, and

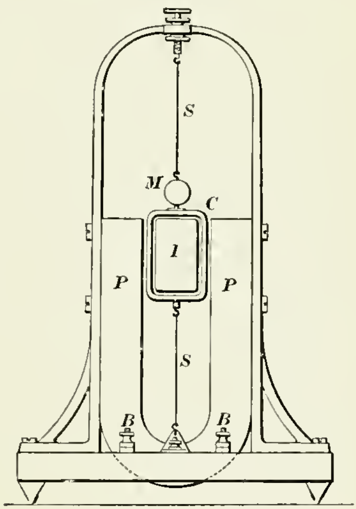

FIG. 9.

consists mainly of a large permanent magnet PP, between the poles of which is suspended a coil of wire C. The current is led to the coil by means of the platinum wires S, S, which suspend the coil, and it will cause the coil to turn in the same manner as a magnetic needle, and for the same reasons. The magnetic lines of force produced in the coil will tend to place themselves, and therefore the coil, in a position where they will be parallel with those of the magnet, and run in the same direction. The coil would therefore adjust itself at right angles to

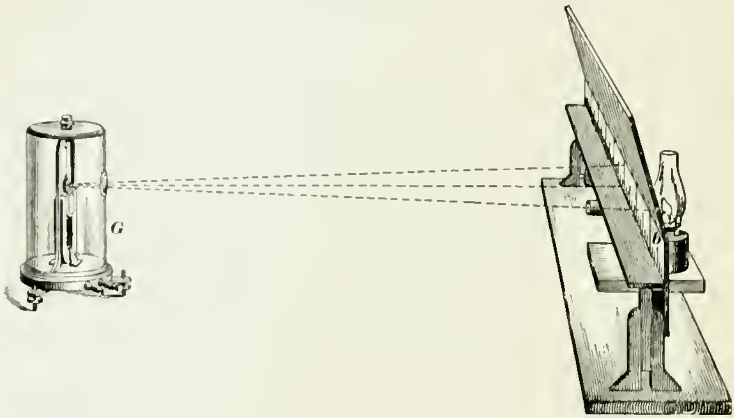

Fig. 10.

its present position, if this tendency were not opposed by the suspension, which may be a spring or an elastic wire. A pointer may be attached to the coil to indicate its deflection, though usually a mirror M is used, a reflected beam of light from which forms the pointer, as will be shown by means of Fig. 10. In many forms of this instrument a soft-iron core I is supported between the poles of the magnet, a space being left between the core and the magnet in which the coil swings. This core serves to reduce the reluctance of the air-space, and the strength of the field will therefore be increased in proportion.

By suitably shaping the poles of the magnet, the intensity of the magnetic field, in various parts, may be so varied that the movement of the beam of light will be directly proportional to the current in the coil.

Connection from the binding-posts *B*, *B* to the coil *C* is made through the platinum wires *S*, *S*. One of the chief advantages of this instrument is the fact that external fields, such as the earth's magnetism, have little effect upon it, so that it requires no controlling magnet or correction for the earth's field, and it may be used near dynamos or large masses of iron without being affected. In Fig. 10 the galvanometer *G* is shown in combination with a lamp and scale, on which a reflected image of the lamp frame will move back and forth. Under the scale *b* is a little lens tube, with a short piece of wire placed vertically across the tube. The light from the lamp is, by means of the galvanometer mirror, reflected on the scale *b*, where the cross-wire will show itself as a dark line on a light spot. If the mirror moves through an angle of 1°, the light beam will move through an angle of 2°, and the galvanometer will therefore be able to indicate most minute currents. In some galvanometers it is thus possible to indicate the pressure of 1 *micro-ampere* by the motion of the light through a distance of about .04 inch.

11. The Weston Milliammeter.—The *Weston milliammeter*, shown in Fig. 11, is made on the same principle as the D'Arsonval galvanometer, and is among the best known forms of portable instruments. Fig. 12 gives a detailed view of the coil and pole-pieces, partly broken away, and Fig. 13 a separate view of the magnet and stationary core. The permanent magnet *A A* has soft-iron pole-pieces *P*, *P* fastened to it by the screws *S*, *S*, and bored out to make a cylindrical opening. In the center of this opening is a stationary soft-iron cylinder *C*, supported in place by a screw *M* passing through a lug on the brass plate *B*. The cylinder being of less diameter than the opening through the

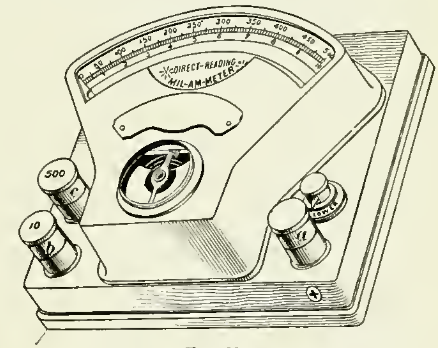

FIG. 11.

pole-pieces, there is left a narrow gap between the pole-pieces and the iron core, as shown. The lines of force from the permanent magnet pass across this space, making a strong and uniform magnetic field.

The movable part of the instrument is shown in Fig. 14. It consists of a rectangular coil *C* of fine wire, wound on an aluminum or thin copper bobbin, which is suspended vertically between two delicate jeweled bearings. Two flat horizontal

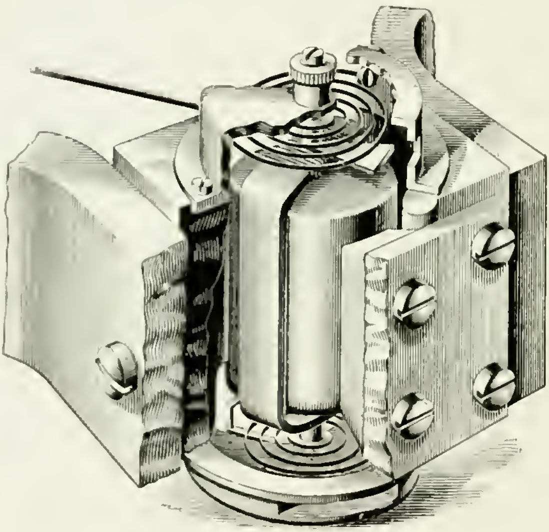

FIG. 12.

springs *S*, *S* oppose the tendency of the coil to rotate, and at the same time conduct the current to the suspended coil.

A thin aluminum pointer *P*, attached at right angles to the coil, moves over the scale and indicates the deflection of the coil from its normal position, which is as shown in Fig. 11. On a current being sent through the coil, the latter will move until the torsion of the springs equals the force with which the coil tends to move, when the coil will come to rest and the pointer will indicate the angle of deflection of the coil.

The copper or aluminum bobbin on which the coil is wound, in moving through the magnetic field, has an electromotive

force set up in it, which causes a so-called Foucault current, already mentioned in Art. **72**, *Magnetism and Electromagnetism*, to circulate around the bobbin, so long as the latter is in motion. This current circulates in an opposite direction to that in the coil; hence, it tends to oppose the motion of the coil, and has the effect of preventing the needle from swinging too far over the scale, thus bringing it quickly to rest at the proper point. When an instrument possesses this quality it is known as a *dead-beat* instrument. It is a very important feature, and one that materially increases the rapidity of taking measurements.

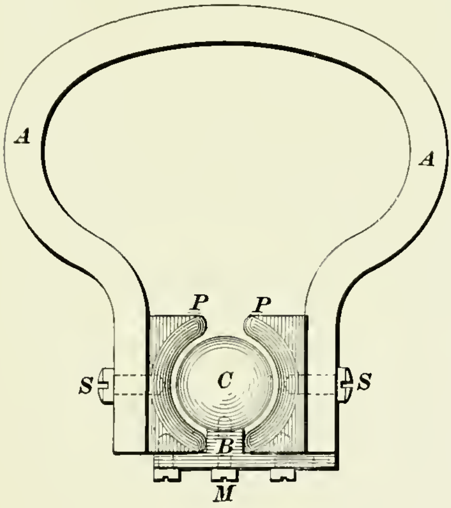

FIG. 13.

The instrument has two scales. When the terminals *a* and *b* are used, the lower of the two scales is to be applied, the instrument then reading up to 10 milliamperes. If currents up to 500 milliamperes are to be indicated by means of the upper scale, the terminals *a* and *c* are connected up.

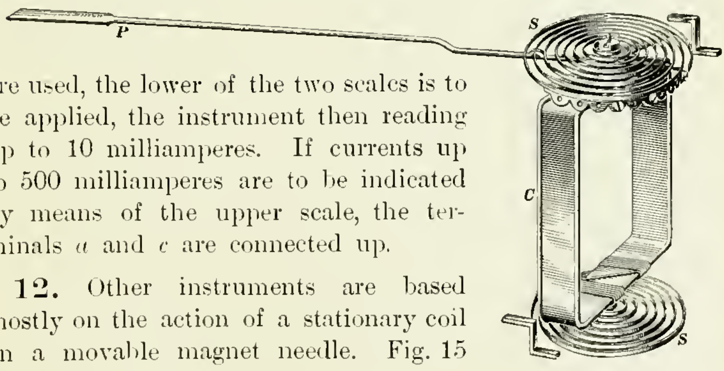

FIG. 14.

12. Other instruments are based mostly on the action of a stationary coil on a movable magnet needle. Fig. 15 shows an instrument of this class, in which the needle is vertical.

For the measurements of pressure or voltage, instruments

very similar to those already described are used. The moving system is practically the same for all direct-current Weston ammeters and voltmeters.

SIMILARITY OF AMMETERS AND VOLTMETERS.

13. Analogy From Hydraulics.—The similarity existing between ammeters and voltmeters, and the possibility of substituting one for the other, is a circumstance that is very difficult for beginners to understand. That an instrument which serves to indicate current-strength in one position can indicate current-pressure in another, seems to be an incongruity. It is not that there is any intrinsic difference between the two instruments; it is rather their different positions relative to the circuit to be tested that makes it possible for them to indicate amperes in one position and volts in another. An analogy from hydraulics will perhaps help to clear this matter up. For instance, let $a\,a_1\,a_2\,a_3$, etc., Fig. 16, be a pipe of large diameter, through which a certain volume of water is constantly flowing. If a small paddle, or vane c, be suspended somewhere in the tube, in the path of the current, and forced to a zero position by means of a spiral spring s, the deflection of the vane would depend on the current-strength, and could be indicated by means of a pointer on a scale. By measuring the number of gallons passing the vane c, by use of a water-meter, the former may easily be made to register the flow in gallons per second, and its function would correspond to that of an *ammeter* when measuring the strength of an electric current.

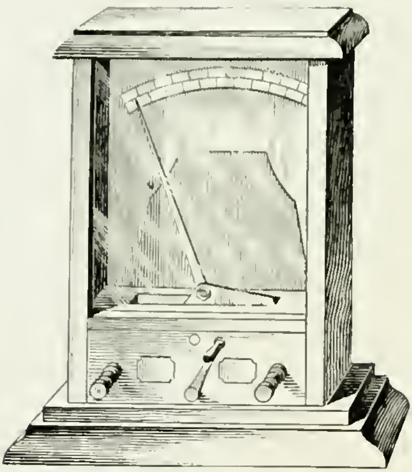

FIG. 15.

14. We will now see how the same vane may be utilized for indicating the pressure with which water is propelled through the part of the tube marked $a_1 a_2 a_3 a_4$. Evidently this pressure is similar to the E. M. F. of an electric circuit. The pressure at a_4 must be lower than at a_1, and the differenec between these two pressures is the pressure required to force the water through the part of the circuit included between these two points. If, now, we establish a current between the points a_1 and a_4 by means of a tube b, water will flow through the latter, for obvious reasons. Such a connection would correspond to what, in electric circuits, is called a "short circuit." In other words, the water would have an opportunity of going either partly or wholly through the tube b, and would therefore affect the indications of the vane c. To obviate this, the tube b is made so small

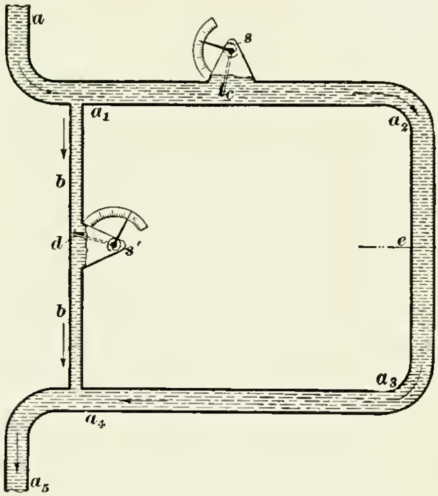

FIG. 16.

in diameter that the current passing through it is insignificant in comparison with the main current, but large enough to operate the vane d placed in its path. The vane d will now revolve in the same manner as c, and for the same reasons; but there is this difference: while the latter vane is operated by the whole current, the former receives only part of it. The greater the difference in pressure between the points a_1 and a_4, the more water will flow through the tube b and the farther will the vane d be deflected. The relation between these deflections and the excess of pressure at a_1 over that at a_4 may be determined, and we then have in the vane d an instrument similar to a *voltmeter*. If the flow of water past the vane c were stopped by closing a valve situated at e, the vane d would still

be able to register the difference in pressure between the points a_1 and a_4, as a current would continue to flow through the tube b and thus deflect the vane d.

15. It would seem reasonable to think that, if this vane d can indicate the difference of pressure between a_1 and a_4, it should also be able to indicate, by means of a separate scale, the current-strength around the circuit $a_1\,a_2\,a_3$ and a_4, because the latter is proportional to this difference of pressure. But it must be remembered that the required surplus pressure at a_1 will not only depend on the strength of the current, but also on the resistance of this part of the circuit. In fact, the tube may either be very long, with a small current, or short, with a heavy current; the instrument at d will make no distinction between these two combinations. If the resistance of this circuit were constant, then the vane d might also indicate the current-strength, as the latter would be directly proportional to the pressure.

16. Ammeter and Voltmeter in an Electric Circuit. It will now be easier to understand the relation between a voltmeter and an ammeter in an electric circuit, and how one

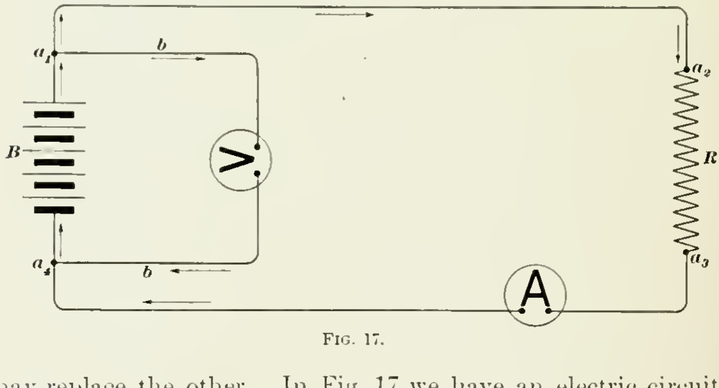

FIG. 17.

may replace the other. In Fig. 17 we have an electric circuit very similar in its general arrangement to the hydraulic circuit of Fig. 16. B is a voltaic battery sending a current through the conductor $a_1\,a_2$, through an external resistance R, and then through the conductor $a_3\,a_4$ back to the battery. In the main

circuit is inserted a milliammeter A in series, while, in the branch circuit $b\, b$, a voltmeter V is placed in parallel with the battery. The whole current is therefore passing through the milliammeter, and its strength is there indicated in milliamperes; only a small portion of the current passes through the voltmeter, and there its pressure is indicated in volts.

17. By virtue of their position in the circuit, it is clear that in one respect they must differ widely from each other. Take, for instance, the milliammeter, which is so situated that it receives the whole current. Evidently, it would materially lower the efficiency of the whole circuit if this instrument were in possession of a high resistance, with the resultant loss of voltage. The resistance must therefore be made as low as possible; in fact, so low that if the instrument is in circuit for days there would be no perceptible heating of its coils. This we also find to be the case with efficient meters; thus, for instance, a 15-ampere Weston ammeter has an internal resistance of .0022 ohm. When measuring a 10-ampere current, the drop $(C \times R)$ is .022 volt, and the watts expended $(C \times E)$ = .22, or about $\frac{1}{3400}$ of a horsepower.

18. With the voltmeter the requirements are exactly the opposite; the resistance must be as high as possible, consistent with an efficient action of the instrument. If the resistance of the voltmeter were as low as that of the milliammeter, the greater part of the current would pass around the battery through the conductors b, b and would thus act as a short circuit. The resistance of a Weston voltmeter is about 19,000 ohms. Measuring 110 volts, the instrument would take $\frac{110}{19000} = .0058$ ampere, nearly, with a consumption of energy of .638 watt, nearly, or about $\frac{1}{1200}$ of a horsepower.

19. It may be suggested that the voltmeter in the position indicated in Fig. 17 should also be able to act as an ammeter by using an additional scale, it being claimed that the current is proportional to the pressure in volts. But it must be remembered that while the current-strength depends on the pressure it also depends on the resistance. For instance, let the resistance R, Fig. 17, be 50 ohms and the current-strength 500

milliamperes; then the required voltage would be $C \times R = 500 \times 50 = 25$ volts. The voltmeter would indicate this pressure, but we see at once that this E. M. F. would also be sufficient to send a current of 2 amperes through a resistance of 12.5 ohms; in fact, these two factors may vary between wide limits, so long as their product remains 25 volts. It is seen, therefore, that, for a voltmeter to indicate amperes, it must be in circuit with a constant or known resistance. This principle is made use of in the Weston ammeter, which makes it necessary to let the whole current go through the movable coil. The latter is connected in parallel with a short, thick piece of copper or some alloy (see a, Fig. 18) so that only a small part of the current passes through the coil, and the resistance of the instrument is extremely low. The ammeter is then more in the position of a voltmeter in parallel with a circuit of constant resistance, and now in reality measures the loss of voltage in the piece of copper a, where a_3 and a_4 are the two ends of the circuit, C the movable coil, and S, S the conductors connecting the coil in parallel with the main circuit. The loss of potential in a will now be in direct proportion to the strength of the current through the strip a; and, as this loss determines the difference in potential between a_3 and a_4 upon which the current through C depends, it is clearly seen that this current is directly proportional to the main current. Thus, while the coil C might operate as a voltmeter for the local conductor a, it will also serve as an ammeter for the whole circuit of Fig. 17, if properly calibrated.

20. We then come to the conclusion that ammeters and voltmeters are in reality both ammeters; that is, they are instruments actuated by an electric current passing through a movable coil placed near a stationary magnet, or through a stationary coil acting on a movable magnetic needle. In the *ammeter* proper the strength of this current depends on the E. M. F. and the resistance of the whole circuit of which the ammeter forms a part; it may also depend on a certain fixed portion of the total current for its operation, when the ammeter constitutes part of a parallel circuit.

21. In the *voltmeter* the strength of the actuating current depends on the difference of potential between the points to which it is attached and the resistance of the local circuit formed by the voltmeter and its connections. We see, then, that the voltmeter is similar to an ammeter when this is provided with a local resistance, as shown in Fig. 18.

22. An Ammeter Changed Into a Voltmeter.—An ammeter of this class should therefore be capable of being transformed into a voltmeter by adding enough resistance to retain the original calibration, but reading volts instead of amperes.

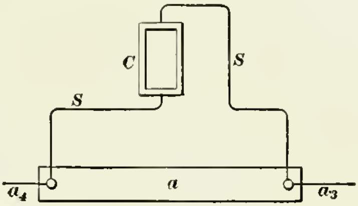

FIG. 18.

An example will illustrate this. A milliammeter has a resistance of 20 ohms. If the meter is to serve as a voltmeter and the divisions in milliamperes are to be read as volts, what external resistance must be added?

It is supposed that the ammeter at present measures up to 1 ampere. The resistance being 20 ohms, it requires an E. M. F. of $C \times R = 1 \times 20 = 20$ volts to bring the pointer to indicate 1,000 milliamperes. To be capable of registering 1,000 volts, the resistance must be increased to 1,000 ohms, as then, according to formula $E = C \times R$, 1,000 volts $=$ 1 ampere $\times$ 1,000 ohms. The required addition to the present resistance is therefore $1,000 - 20 = 980$ ohms.

If the instrument shall read to 100 volts only, then, placing $E = 100$ volts, we have $R = \frac{E}{C} = \frac{100}{1} = 100$ ohms, and the needed addition will be $100 - 20 = 80$ ohms. In this instance every 10 divisions of milliamperes will represent 1 volt.

23. Difference Between Ammeters and Voltmeters. Before leaving the subject of ammeters and voltmeters, there is yet one point to mention, which is not always understood. Why is it, for instance, that an ammeter can be short-circuited with impunity, but cannot be removed from the circuit, while a

voltmeter must not under any circumstances be short-circuited, but may be disconnected? Let the diagram in Fig. 19 show a voltaic battery combined with an electric bath. The resistance of the circuit is 90 ohms, the E. M. F. 30 volts, and therefore the current $C = \frac{E}{R} = \frac{30}{90} = .333$ ampere. B is the voltaic battery, a_1 the conductor sending the current to the bath C, and a_2 the return circuit. The milliammeter A is placed in series with the conductor a_1, and the voltmeter V in parallel with the bath by means of the conductor $b\,b$. It is now seen that the whole current passes through the milliammeter A before it reaches the bath, and that by disconnecting this instrument the circuit would be broken and the current stop its flow. If, on the other hand, the milliammeter be short-circuited by means of the

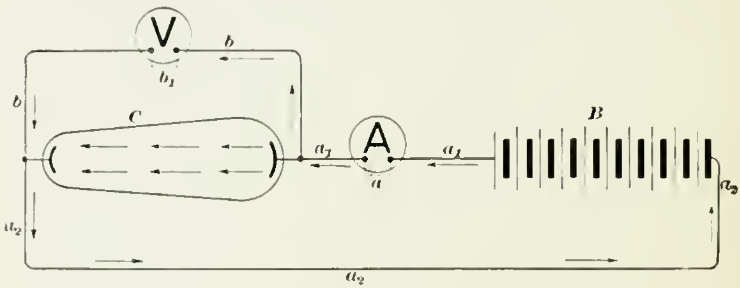

Fig. 19.

additional conductor a, it would have no influence on the circuit as a whole, the resistance of the instrument already being so low as to be left out of consideration, but would rather have the effect of removing the instrument from the circuit.

24. With the voltmeter we find the opposite to be the case. Here a removal of the voltmeter would leave the rest of the circuit unaltered, and the current would continue to flow through the bath; but let the voltmeter be short-circuited by means of the conductor b_1, then the conductor b would no longer be limited in its conductivity by means of the high resistance of the voltmeter, and would tend to carry the whole current of the battery. It would, therefore, short-circuit the bath and consequently also the battery, and would very likely

injure the latter; otherwise, the damage might be little. When it comes to circuits with higher voltage and amperage, as, for instance, in a lighting circuit, the consequences would be more serious.

In Fig. 20 we have, for instance, the conductors a_1 and a_2 leading to a combination of incandescent lamps L in a house.

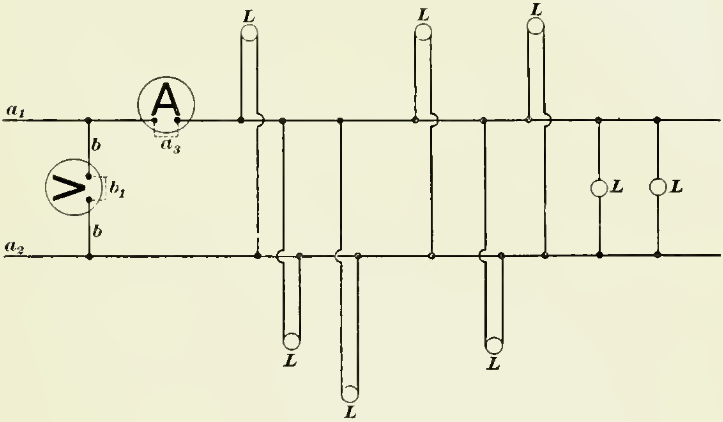

Fig. 20.

The lamps are all placed in parallel and the ammeter A inserted in the conductor a_1, while the voltmeter V, by means of wires b, b is connected with both conductors, and therefore is in parallel with the lamps. If, now, the ammeter be again short-circuited by the wire a_3, it will have no effect on the circuit, but will simply throw the ammeter out of action, whereas removing the ammeter altogether, before being short-circuited, would, of course, break the circuit and extinguish all the lamps.

A short-circuit of the voltmeter by means of the wire b_1 would not only affect the lamps in this house but in the whole neighborhood. It would send a very strong current across the conductors b, b_1, b, and either melt these wires or the safety-fuse which may be situated there. A fuse consists of a strip of metal through which an ordinary current will pass unimpeded, but which will heat and melt if the strength of the current goes beyond certain determined limits; it will, therefore, break the circuit and prevent any serious damage to the rest of the

apparatus. Disconnecting one of the wires leading to the voltmeter, while in circuit, will have no other effect than simply removing the instrument from the circuit.

RHEOSTATS.

25. We have now seen how, by means of a voltmeter and an ammeter, the qualities of an electric current flowing in a circuit may be ascertained. There is still another instrument used in combination with these two, which serves to alter the current-strength, if the pointer of the ammeter does not indicate the desired amperage. It has been shown that the latter can be varied by altering either the voltage or the resistance. If using a voltaic battery, the cell-selector was able to change the E. M. F. by altering the number of cells in circuit; but it was shown that, when finer gradations were desired, it required the insertion of an external resistance. Metallic wires, carbon, water, or other substances are used for this purpose, and instruments of which they constitute a part are called *rheostats.*

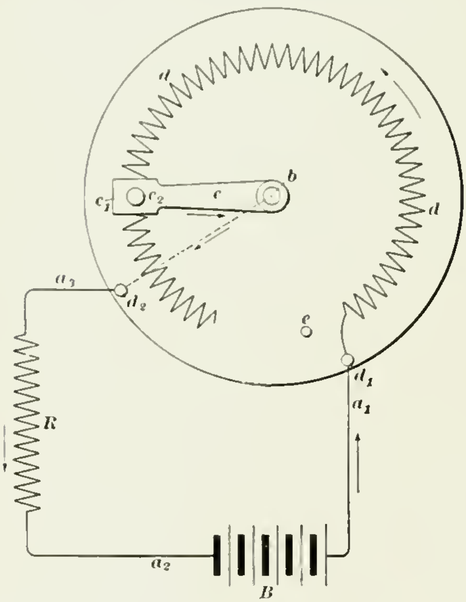

Fig. 21.

When these rheostats are used in connection with circuits carrying heavy currents, it is customary to make the resistance of metallic wires either of German silver or iron; but where it is necessary to regulate small currents only, as in electrotherapeutics, then carbon or water, or a combination of the two, are mostly used.

26. Wire Rheostat.—The principle generally utilized in these rheostats is shown diagrammatically by means of Fig. 21. Here a wire coil d made of German silver is laid out in the shape of a circle, and in this form is fastened to some suitable base. The battery B is connected to the terminals d_1 and d_2 by means of the conductors a_1, a_2, external resistance R, and conductor a_3. The lever c pivoted on the stud b is broadened at its peripheral end c_1, and carries there a handle c_2 by means of which the lever may be moved over the resistance-coil on either side of the stop e. It will be seen that if the lever is pushed against the left side of said stop the circuit is broken. By moving the lever in a clockwise direction, it will come in contact with the coil d, and the current will then flow through the whole length of the latter before it reaches the lever and can pass through this to the stud b and terminal d_2. If the motion of the lever is continued, the length of the resisting path will be decreased, and therefore also the resistance, until, when the stud e is reached, the whole resistance is cut out and the whole voltage of the battery utilized in sending a current through the external resistance R. Of course, the lever will be moved in either direction until a resistance is found sufficient to reduce the current to the desired strength.

27. Carbon Rheostat.—Most of the rheostats are simply variations of this form, in which the resistance-coil is replaced

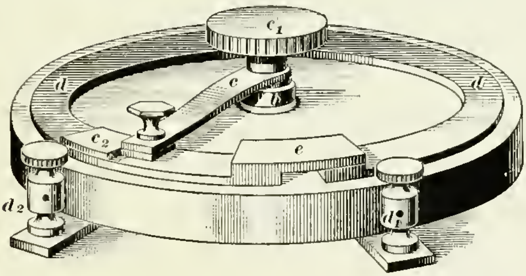

FIG. 22.

by a resisting path made either of carbon or mixtures of carbon with some other material. In Fig. 22 is a rheostat made of slate, in which the parts corresponding to those in Fig. 21 are

designated by the same letters. The upper surface of the ring *d*, made of slate, is rubbed with an ordinary soft pencil. The carbon deposited in this manner serves as a path for a current of fairly high resistance, and the length of this path is varied by placing the lever *c*, with the copper brush c_2, at various distances from the stop *e*. This layer of graphite needs to be renewed at intervals by being rubbed over again with a pencil; in the same way the total resistance of the path can be decreased by depositing a thicker layer of graphite on the same. There are also other forms of carbon rheostats more or less resembling the one described.

28. Carbon Pressure Rheostat.—A rheostat, based on a somewhat different principle, consists of a column of carbon powder, through the whole length of which the current is compelled to flow. Its resistance is varied by subjecting the column to more or less pressure; an increase of pressure brings the carbon particles in closer contact and decreases the resistance.

29. Bailey's Rheostat.—A combination of carbon and water is used in the rheostat shown in Fig. 23. *A* is a glass vessel, partly filled with water, *d*, *d* two triangular pieces of carbon supported by two rods *f*, *f*, which carry binding-posts d_1, d_2 at one extremity and pinions c_1, c_2 at the other. Both of the latter engage with a worm provided with a milled head *c*. At the point of each carbon is a sponge *s* which constantly dips into the water, and thus makes the closing of the circuit more gradual. The conductors g_1, g_2 communicate with the carbons,

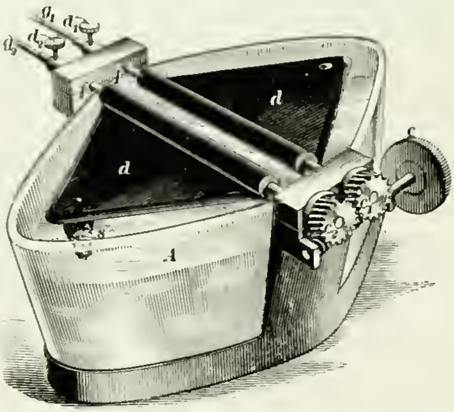

FIG. 23.

and by turning the head c the carbons are made to dip more or less deeply into the water, thereby simultaneously increasing the sectional area and decreasing the length of the water-column situated between the two carbons.

30. Fluid Rheostat.—Another fluid rheostat is illustrated in Fig. 24. A is a glass cylinder filled with a liquid of a certain specific resistance, depending on the voltage of the circuit. The cylinder is inserted in the base b and provided with a cap c. Through the base projects the rod d, which terminates in the ball d_1; at its other extremity it has a binding-post g_2. The current enters through the latter, and leaves the terminal d_1 to continue its passage through the liquid column until it meets the other terminal e_1, when it flows through the rod e into the cap c and out through the binding-post g_1. The resistance is increased by turning the milled head f in a direction that will compel the threaded rod e to rise and thus increase the distance between the terminals d_1 and e_1. A rheostat of this form may be used in combination with an influence-machine, and control a current with more than 20,000 volts pressure.

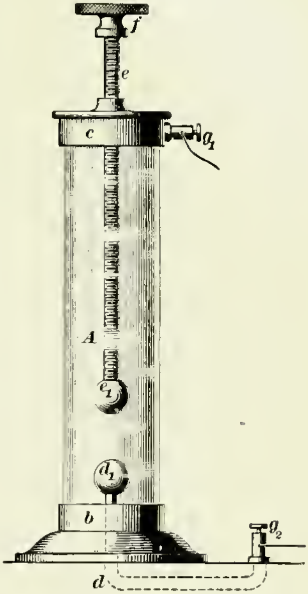

FIG. 24.

INFLUENCE OF RESISTANCE ON E. M. F. AND CURRENT.

31. After the functions of the voltmeter, ammeter, and rheostat have been studied separately, it remains yet to be seen how these instruments work in conjunction with each other. The effect which the rheostat has on the various parts of a circuit is a subject that is not clearly understood by beginners, and therefore requires some explanation, particularly as the rheostat plays such an important part in electrotherapeutics.

The question to be answered is this: Does the rheostat affect the current-strength only, or does it also affect the pressure at the battery terminals?

If this question were to be answered off-hand, it would seem, as a matter of course, that any resistance the rheostat might insert in the circuit would merely increase the total resistance of the latter, and therefore diminish the current-strength. A closer study of the condition will show that this answer is not quite correct, but that an increase of the resistance does in fact increase the *available* E. M. F. at the battery terminals. Of course, this does not mean that it increases the *total* E. M. F. generated by the battery; on the contrary, this E. M. F. remains practically constant, so long as we deal with voltaic batteries and not with dynamos or other generators.

32. Some practical examples, illustrated by means of Figs. 25, 26, 27, 28, and 29 will make the reasons for this perfectly clear.

Let the battery B in Fig. 25, consist of 10 cells, each of an

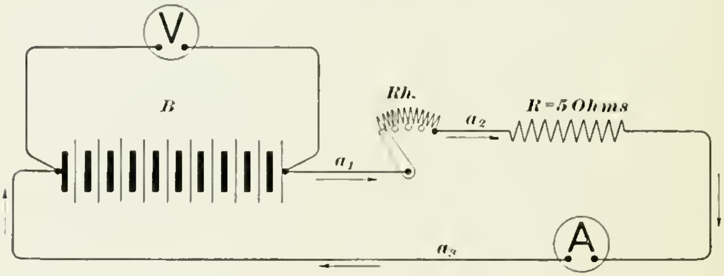

FIG. 25.

E. M. F of 1.2 volts and an internal resistance of .5 ohm. The total E. M. F. of all the cells in series will therefore be $10 \times 1.2 = 12$ volts, and the total internal resistance $10 \times .5 = 5$ ohms.

In the same figure, R is an external resistance of 5 ohms, and $Rh.$ a rheostat, which, by means of the conductors a_1 and a_2, connects, respectively, with the battery and the resistance R; the conductor a_3 returns the current from the latter to the battery. A voltmeter and a milliammeter complete the arrangement.

It is the purpose, by means of this combination, to send a current from the battery B through the external resistance R, which latter may, for instance, be the resistance existing between two electrodes applied to the human body for some local treatment. The number of amperes that will flow through this external resistance is to be controlled by means of the rheostat.

33. When no resistance is inserted by the rheostat, and the only resistances in circuit are those of the battery and the human body, the conditions will be those represented in Fig. 26. Here we find the whole circuit of Fig. 25 extended along a horizontal line $a\,h$, representing zero potential, and the parts marked off in the same order as in the former figure. It is supposed that the point h connects directly with the point a, and that the various

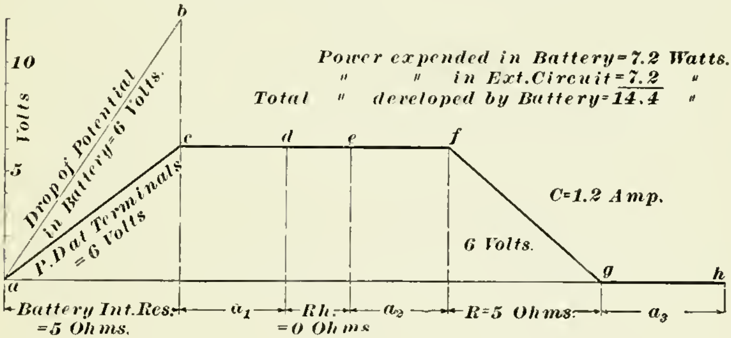

FIG. 26.

divisions marked with the letters a_1, $Rh.$, a_2, etc. correspond to the parts marked with similar letters in Fig. 25. It is also supposed that the conductors a_1, a_2, and a_3 are of such ample cross-sectional areas that the drop of potential taking place in them may be left out of consideration.

Beginning, then, with Fig. 26, we find, as the only resistances in circuit are the 5 ohms of the battery and the 5 ohms external resistance, that the strength of the current will be $C = \frac{E}{R} = \frac{12}{5 + 5} = 1.2$ amperes. At the left end of the figure the line $a\,b$ indicates a rise of potential of 12 volts, which

would take place if the battery were devoid of internal resistance. But a current of 1.2 amperes having to pass through its resistance of 5 ohms, the current suffers a loss in potential of $C \times R = 5 \times 1.2 = 6$ volts. The potential difference at the terminals of the battery will therefore be $12 - 6 = 6$ volts only, as represented by the line *a c*, and this is the pressure that will have to carry the current through the rest of the circuit. No resistance being inserted by the rheostat, and the resistances of the conductors a_1 and a_2 being left out of consideration, the potential of the current will remain unaltered while passing through them, and the lines *c d*, *d e*, and *e f*, representing the potential of these parts, will be lines parallel with the zero-line *a h*. At *f* the current enters the external resistance R of 5 ohms, and here suffers a loss of pressure amounting to $C \times R = 1.2 \times 5 = 6$ volts. This means that the whole available pressure of the battery has been consumed in the resistance R, and that the current now, through the conductor a_3, again enters the battery at zero potential.

34. It has been shown in Art. **134**, *Direct Currents*, that a battery gives a maximum power to an external circuit, when the resistance of said circuit is the same as that of the battery. As this corresponds with the conditions found in Fig. 26, we shall expect to here find a maximum power spent in the resistance R. The power expended on the various parts of the circuit is found by multiplying the loss of potential that the current suffers in passing through them by the strength of the current in amperes. The total power developed by the battery is $E \times C = 12 \times 1.2 = 14.4$ watts. That part of the total power which is spent in the battery itself we find by multiplying the drop of potential in it by the current, or $6 \times 1.2 = 7.2$ watts. The external resistance R being equal to that of the battery, the drop will be the same, and therefore, also, the power consumed. We see, then, that, of the total power of 14.4 watts, 7.2 watts have been spent, respectively, in the battery and in the external circuit.

If the battery had been short-circuited, the total power developed would have been greater, but of course none of it

would have been available outside of the battery. The current C that would circulate through the latter, in this instance, would have a strength of $\frac{E}{R} = \frac{12}{5} = 2.4$ amperes, and therefore a power of $E \times C = 12 \times 2.4 = 28.8$ watts.

35. In Fig. 27 the conditions are altered, for, by means of the rheostat, a resistance of 5 ohms has been inserted, making a total of $5 + 5 + 5 = 15$ ohms. The current-strength will now be $\frac{E}{R} = \frac{12}{15} = .8$ ampere, which is 33 per cent. less than that of the circuit shown in Fig. 26.

The strength of the current having decreased, it follows as a consequence that the loss of potential in the various parts of

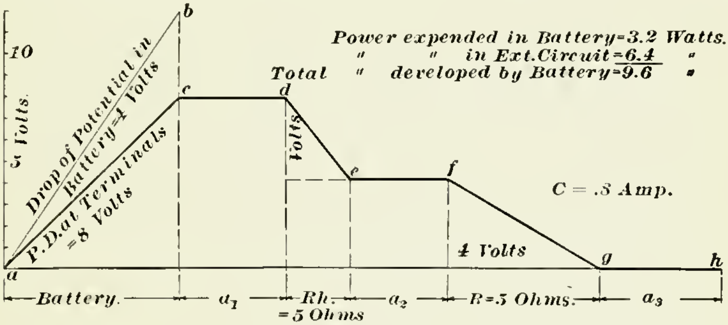

FIG. 27.

the circuit must also decrease, as these losses are products of current and resistance.

When we now calculate the loss of potential in the battery, it is found to be $C \times R = .8 \times 5 = 4$ volts, or 2 volts less than in Fig. 26; consequently the available E. M. F. at the terminals of the battery, or $12 - 4 = 8$ volts, must be larger than that previously at our disposal. Following the distribution of these 8 volts over the remainder of the circuit, we find, as before, that the current, while flowing through the conductor cd, suffers no loss of potential, but that, on passing through the 5 ohms resistance of the rheostat, the pressure at once falls from 8 to 4 volts, which pressure remains throughout the conductor ef; after leaving the latter the current again suffers a

loss of 4 volts, caused by the 5 ohms resistance of the external resistance R.

Comparing the two examples, illustrated by means of Figs. 26 and 27, it is seen that the insertion of the rheostat resistance of 5 ohms has the effect of raising the available E. M. F. at the battery terminals from 6 to 8 volts, but that notwithstanding this increase the current-strength decreased from 1.2 amperes to .8 ampere. If the resistance and E. M. F. had increased in the same proportion, the current-strength would have remained the same; in this instance the exterior resistance is increased by 100 per cent. and the terminal E. M. F. by 33 per cent. only; the latter, therefore, did not keep

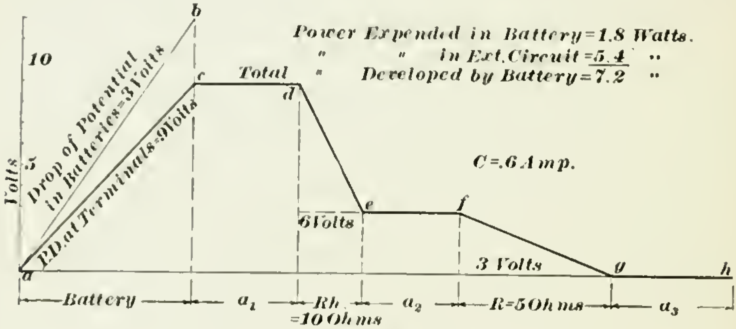

FIG. 28.

step with the former, with the result that the current decreased. Had the terminal E. M. F. remained the same as before, the current would have been .6 ampere only; but, being increased by 33 per cent., the amperage rose from .6 to .8 ampere.

We come, then, to the conclusion that increasing the resistance in the external circuit of a battery does not decrease the current in the same proportion, because the available E. M. F. increases simultaneously, though not in the same ratio.

36. In Fig. 28 the resistance of the rheostat is increased to 10 ohms and the current has now decreased to $\frac{E}{R} = \frac{12}{20} = .6$ ampere, while the drop of potential in the battery is 3 volts only, and therefore the available E. M. F. $= 12 - 3 = 9$ volts.

The other losses in the circuit can easily be seen by the data given in the figure.

37. As a final example of the influence exerted by the rheostat, we will consider the circuit illustrated by means of Fig. 29. Here the rheostat has increased its resistance to 30 ohms, making a total resistance for the whole circuit of 40 ohms. The current has now fallen to $\frac{E}{R} = \frac{12}{40} = .3$ ampere. At the same time the loss of potential suffered in the battery has decreased to 1.5 volts, which leaves an available

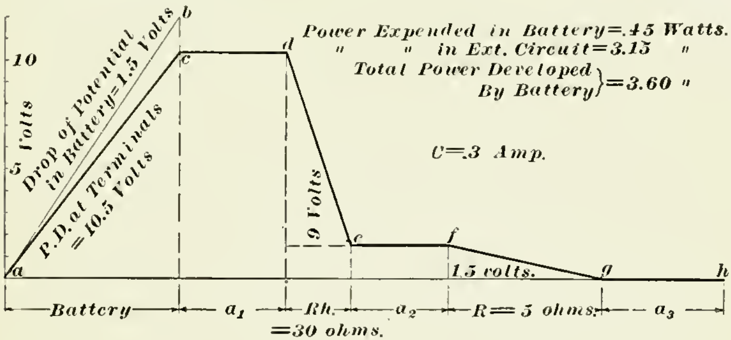

Fig. 29.

pressure at the terminals of $12 - 1.5 = 10.5$ volts. In the rheostat the loss is now 9 volts, while in the permanent resistance R it is 1.5 volts only. This last example brings out more clearly another feature, that an increase of the resistance in the circuit external to the battery will bring the available pressure at the terminals nearer to the total E. M. F of the battery, and at the same time the current will decrease in strength. Finally, the resistance will be so great that the current practically stops altogether; the circuit is then in the same condition as when open, and the pressure at the battery terminals will be identical with the total E. M. F.

38. Data relating to the power spent in the external circuit are given in each figure. It is at once seen that the power has reached its maximum value when the conditions are as shown by Fig. 26, that is, when the external resistance is equal to that

of the battery. An increase or decrease of the resistance in the external circuit will have the same result—that of decreasing the available power. Simultaneously with the decrease of the current the number of watts spent outside of the battery will also decrease until, in Fig. 29, the power spent has the value of 3.15 watts only.

39. The condition that must prevail if maximum power is to be given an external circuit may also be expressed in another way, by saying that, if a voltmeter, connected with a battery as in Fig. 25, indicates a pressure of one-half of the total E. M. F of the battery, maximum work is being done in the external circuit. This of course does not mean that the resistance, outside of the battery, may be increased by means of a rheostat until the desired value of the terminal pressure is reached. It is true that in this case also maximum power is given to the circuit, but the resistance *R* receives only a small fraction of it, the greater part being uselessly wasted in the rheostat, where the electrical energy is changed into mechanical energy in the form of heat. It is therefore clear that, if a device external to the battery is to receive a maximum power from the battery, this device itself must constitute the external resistance.

DYNAMOS, MOTORS, AND TRANSFORMERS.

DYNAMOS.

FUNDAMENTAL PRINCIPLES.

40. Conversion of Mechanical Into Electrical Energy.—In the voltaic cell we have seen a source of electromotive force, in which chemical energy was changed into electrical energy. Under certain conditions this source was found satisfactory, but where the supply was to be continuous and the output in watts large, it would, in addition to being inconvenient, also be very expensive. Under these conditions

the advantage lies with a source of electromotive force in which *mechanical* energy is changed into electrical energy.

In *Magnetism and Electromagnetism*, when treating of electromagnetic induction, we observed that a wire moving across a magnetic field, or vice versa, had an E. M. F. created in it. This was taken advantage of in the induction-coil by changing a low E. M. F. into a high one, and was also utilized in the magneto-electric generator for the production of an E. M. F. The latter machine properly belongs in the class where mechanical energy is changed into electrical; but, as the power consumed is so small, and its field of usefulness limited mostly to that of the induction-coil, it was treated in conjunction with the latter.

Fig. 33, *Magnetism and Electromagnetism*, showed the effect of moving a conductor across a magnetic field. It would naturally suggest the idea that a machine built on that principle could be advantageously used for generating an E. M. F. on a larger scale by adding more conductors and moving them at high speed. Since it is, of course, impossible to constantly supply new conductors, provision must be made for returning the conductors to their original positions, and let them repeat their motion through the magnetic field without interfering with the action of the machine.

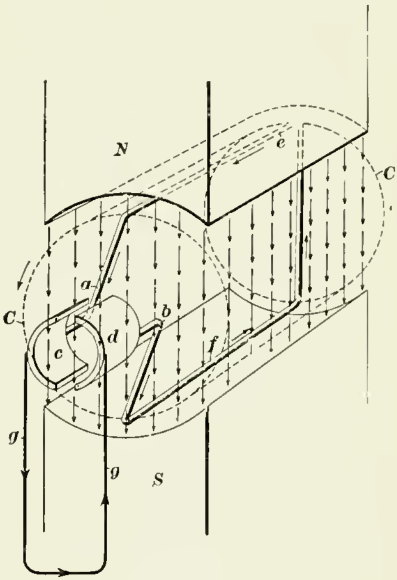

FIG. 30.

These conditions are complied with, if the conductors are arranged along the curved surface of a cylinder or radially along the sides of a disk, and if either of these are set in rotation in a magnetic field. We will consider the cylindrical form only, as shown in Fig. 30.

Here we have a conductor *a e f b* bent along the surface of a cylinder, shown in dotted lines, and rotating with it in the direction shown by the arrows. The ends of the conductor are joined to the segments *c* and *d*. *N* and *S* are the poles of the magnet, and, as *N* is the north pole, the lines of force will pass in the directions indicated by the arrows on the dotted lines. From the rule given in Art. **54**, *Magnetism and Electromagnetism*, we find that the direction of the E. M. F. induced in the lower part *f* of the conductor is as indicated by the arrow, and we also find that the induced E. M. F. in the upper part of the conductor *e* acts in the opposite direction. The result is that the two electromotive forces act in the same direction, so far as the conductor is concerned ; that, therefore, the total E. M. F. will be a sum of two ; and that there is a tendency to start a current in the direction of this E. M. F. If, now, a conductor *g* is held, as indicated, against the segments *c*, *d*, a current will flow through the conductor as indicated.

41. Coil and Commutator.—A step further, to increase the action of the machine, would be to wind the conductor several times around the cylinder, each convolution adding to the E. M. F. ; it constitutes then what is called a *coil*. It is also evident that it would be a waste of space to let the rest of the cylinder lay idle ; that, in fact, it would be natural to provide the whole circumference with conductors, and that each would be connected with segments similar to *c*, *d*, but that the latter would have to be made correspondingly narrower, so as to allow space for the rest. These segments would all be insulated from one another, and form a cylinder called a *commutator*, so named because it commutes currents running in opposite directions into currents running in the same direction, and under certain conditions combines these currents into one uniform current.

Instead of making contact with the commutator by means of a conductor *g*, it is customary to provide two broad plates, either of carbon or of laminated copper. called *brushes*, and let the terminals of the machine be connected with the supports of these brushes.

42. The machine which we so far have described, has one great drawback; there is only one conductor at a time in communication with the brushes. Any electromotive forces that may be generated in the other conductors are useless; they cannot start currents, because their segments are insulated from one another, like *c*, *d*, and, therefore, their circuits open. Even could currents flow, they would be unable to reach the brushes, and would simply waste their energy in their respective circuits. To eliminate this great fault, all the conductors or coils are connected with one another, constituting one large coil.

43. Armature.—As yet, no mention has been made of the cylinder *C* indicated by dotted lines. It could be made of any material, simply acting as a support for the conductors, but it is always made of laminated iron. It is made of iron because iron is a good magnetic conductor, and thus, practically, is a continuation of the magnetic *pole-pieces* *N* and *S*; and it is laminated in order to avoid the starting of Foucault's current, already mentioned in Art. **72**, *Magnetism and Electromagnetism*. This combination of the conductors and an iron cylinder or drum is called an *armature*.

It is not necessary that the conductors shall be supported by a cylinder; they may also be wound around a ring, as shown in Fig. 31, and then constitute a *ring armature*, while the former is called a *drum armature*. The iron ring or drum is the *core*.

44. Ring Armature.—In Fig. 31 we see all the coils a_1, a_2, etc. connected with one another, constituting one coil; we also see the connectors c_1, c_2, etc. connecting the junction of the coils with the commutator segments s_1, s_2, etc. *N* and *S* are the pole-pieces; *N* being the north pole, the lines of force will pass from right to left. The armature-core is marked *b*, and is rotating in the direction indicated by the arrow.

From what has been previously said on the subject, we should easily find that the directions of the induced E. M. F. in the various coils are as indicated by the arrows. We notice now a peculiarity which, at first glance, would seem to make the whole machine inoperative, that the directions of the

electromotive forces on one side of the dotted line $x x$ are acting in opposition to those on the other side. But, after some consideration, we find that the two halves of the armature are, in reality, joined in parallel, and that whatever currents are flowing in either half, combine at the connector c_2, pass through the latter into the segment s_2, and from there through the positive brush d into the conductor f. After passing through the external resistance R, the current returns through the conductor g, into the negative brush e, then through the segment s_6

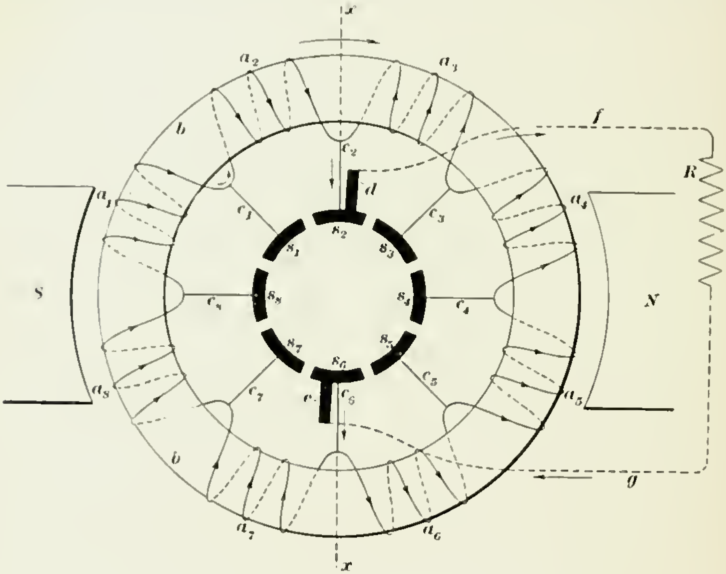

Fig. 21.

and connector c_6, when it divides, one half of the current flowing through the coil a_6 and the other half through the coil a_7. From either of these coils the currents continue their upward flow: but it must be remembered that in the next moment the coils a_6 and a_2 will pass the line $x x$, called the *neutral line*, and that then the current will flow through them in opposite directions. In fact, in each coil the direction of the current flowing through it will be reversed twice for each revolution of the armature.

45. It was stated in Art. **56,** *Magnetism and Electromagnetism*, that the E. M. F produced in a conductor increased in proportion to the density of the field and the speed of the conductor in a direction at right angles to the lines of force. Neither of these factors is constant in regard to the armature of Fig. 31. The coils a_4, a_5, a_1, and a_8 are passing through a denser field than the coils a_2, a_3, a_6, and a_7; the E. M. F. of the former coils will therefore be higher than that of the latter. An additional detriment is that the last-named coils no longer travel in a direction at right angles to the lines of force, but more or less parallel to them, and that, therefore, when approaching the neutral line, smaller and smaller electromotive forces will be produced in them.

46. Armature Compared With Cells in Parallel Series.—How these electromotive forces of varying heights and directions combine so as to produce one current is shown by means of Fig. 32. We have here 10 cells, arranged in two parallel series of 5 cells. There are, therefore, 5 cells on either side of the neutral line $x\,x$, the electromotive forces of the cells at the left running in opposition to those of the cells at the right. The effect is that two currents of electricity will flow, one on either side of the neutral line, and

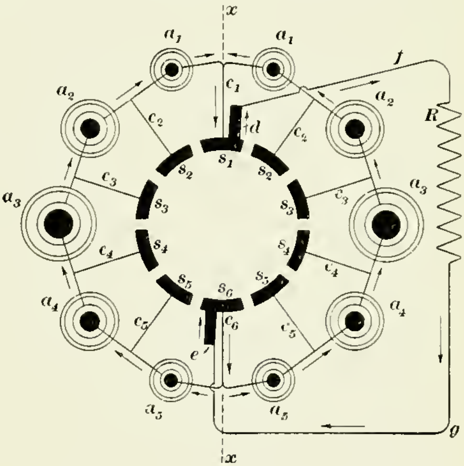

FIG. 32.

that they will meet at c_1, where they unite into one current of double the amperage; it will then flow through the segment s_1 into the positive brush d and the conductor f, through the external resistance R. From here it will again return through the conductor g to the negative brush e, pass through the

segment s_6, when it will divide again into two separate currents flowing through the cells on either side of the line xx to the connector c_1.

If the current, instead of dividing into two branches, had to pass through all of the 10 cells, the loss in voltage would be 10 volts, if we suppose that the internal resistance of a cell is .1 ohm and the current-strength 10 amperes. In the arrangement indicated in Fig. 32, the total resistance of the battery would be (see Art. **128**, *Direct Currents*):

$$r' = \frac{s \times r}{p} = \frac{5 \times .1}{2} = .25 \text{ ohm},$$

and the loss in voltage,

$$E = C \times r' = 10 \times .25 = 2.5 \text{ volts},$$

which is one-quarter of the "drop" with all the cells in series.

It was shown that some of the coils in Fig. 31 developed a higher E. M. F. than others. This has been indicated in Fig. 32 by increasing the size of the cells corresponding in position to those of the coils, when having their maximum E. M. F.; but this must not be understood to mean that an increase of the size of a cell increases its E. M. F. In this instance it must simply be taken as a graphical representation of the relative electromotive forces in the various cells.

47. The diagram in Fig. 32 shows very clearly the result of connecting all the coils in series and connecting all the junctions with the commutator-segments. We see that each cell adds its E. M. F. to that of the preceding cells; the same is done by the coils in Fig. 31. It is also evident from Fig. 32 that the connections between the segments and the coils have no influence on the flow of current, and no function to perform, except in that instance when the segments pass under the brush. The segments s_2, s_3, s_4, and s_5, though joined to the connectors c_2, c_3, etc., cannot transmit any current in the positions there indicated, because, for the moment, they are insulated from the rest of the circuit; all the connectors and segments, except those marked c_1, c_6, and s_1, s_6, might therefore be removed without affecting the operation of the dynamo or cells, so far as

the position indicated is concerned. Of course, when the armature revolves, all the connectors and segments subsequently come in action.

48. Action of a Dynamo.—We are now able to study an assembled view of a *dynamo* and understand its action in general. In Fig. 33 a dynamo is shown in a diagrammatical view. *A* is the armature, *c* the commutator, *d* and *e* the brushes, and *h* the shaft that supports and drives the armature. The shaft is supported in bearings, not shown in the drawing, at both of its ends. *N* and *S* are the pole-pieces, which receive their magnetism from the electromagnets E, E_1, k, l being the coils and i, j the cores of the electromagnets. The upper ends of the cores are connected by an iron block *m* called a *yoke*.

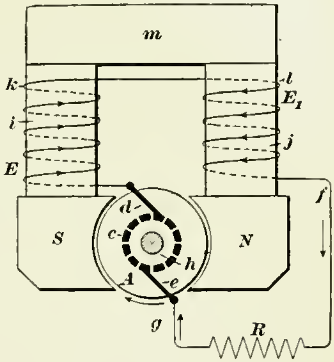

FIG. 33.

The current leaves the positive brush *d* and passes directly into the coil *k*, then from this into the other coil *l* and through the conductor *f* into the external circuit *R*. From here it returns through the conductor *g* and the negative brush *e* to the commutator *c* and the armature *A*. The electromagnets or *field-magnets* as they are usually called, are therefore magnetized by the dynamo itself, and the latter is therefore said to be *self-excited*. If the exciting current of the field-magnets is supplied from some outside source, it is *separately excited*.

CLASSES OF DYNAMOS.

49. Series and Shunt Dynamos.—When the whole current from the armature goes through the field-magnet coils, and they, so to speak, are connected in series, the dynamo is a *series* dynamo (see Fig. 33). If the field-magnet coils and the external circuit are connected in parallel, and therefore only

part of the whole current goes through the field-magnet coils, which, in that case, usually are of high resistance, then it is a *shunt* dynamo (see Fig. 34). Here the current divides into two parts, the smaller passing directly into the field-magnet coils F, F_1, while the balance goes into the external circuit.

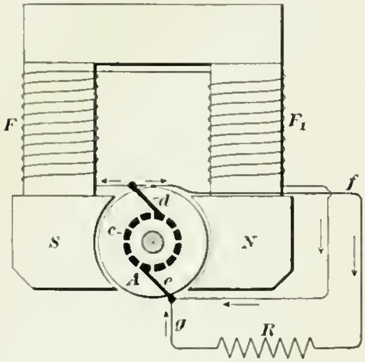

Fig. 34.

50. Compound Dynamo.—When the coils are partly in series and partly in shunt, we have a *compound-wound* dynamo, as shown in Fig. 35.

51. Difference Between Series and Shunt Dynamos.—These variations in combining the coils with the armature are for the purpose of regulation, and are determined by the use for which the dynamo is intended. When, as in Fig. 33, the whole current goes through the field-magnet coils, the flow through the latter will be affected by any variation of resistance in the external circuit R. An increase of resistance will diminish the amperage of said coils and also the strength of the magnetic field. In Fig. 34 the conditions are different. Increasing the external resistance causes an increased flow through the coils F, F_1, and therefore strengthens the magnetic field. The E. M. F. of the armature will then increase, and it will be able to send the same current through an increased resistance, if this remains within certain limits. Fig. 35 is a combination of both, and a dynamo of this character is able to regulate itself within wide limits.

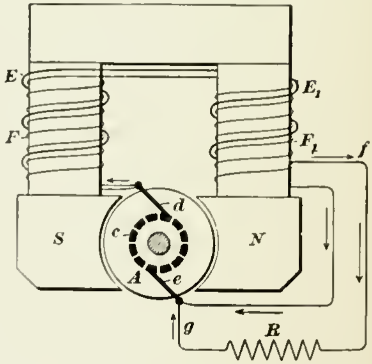

Fig. 35.

52. Alternators.—The dynamos so far considered deliver a continuous current, because the commutator rectifies the various currents in such a manner that they run in the same direction. The dynamo, then, in reality provides an *alternating* current. If we therefore excite the field-magnet coils from some exterior source, remove the commutator and replace it by two simple contact-rings with brushes, we would, if the armature is properly wound, receive an alternating current from the brushes. The machine would then no longer be a dynamo, but an *alternator.*

MOTORS.

53. General Principles.—In Art. **54,** *Magnetism and Electromagnetism*, was described the effects produced in a conductor when moving in a magnetic field, and Fig. 33 illustrated this in a diagrammatic form. If the conditions there represented be reversed and a current sent through the conductor while it is situated in a magnetic field, what would be the result? The conductor would move, but in a direction *opposite* to that which would produce an E. M. F. acting in the same direction as that of the current now flowing. For instance, if, in Fig. 36, the conductor were moving across the field in the direction indicated by the arrow, an E. M. F. would be created that would tend to send a current *down* through the paper. If, on the other hand, it is intended to move the conductor in the same direction by means of a current, sent through it from some external source, then the current has to be sent through it in an *upward* direction. The illustration will show the reasons for this. It is observed that the lines of force, encircling the conductor, and which are produced by the upward passing current, on one side travel in the same direction as the lines of force

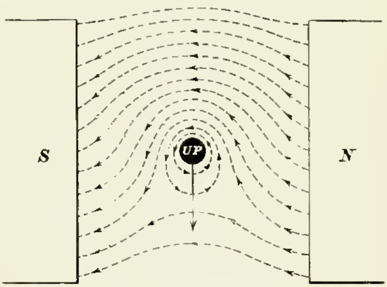

FIG. 36

belonging to the pole-pieces *N*, *S*; a repulsion will therefore take place, for reasons already given in Art. **10**, *Magnetism and Electromagnetism*. On the other side, the lines of force travel in opposite directions and an attraction will be effected. Both of these forces tend to move the conductor in the direction indicated by the arrow. This reaction between an active conductor and a magnetic field is the principle upon which an electric *motor* is based.

It is therefore possible to change any dynamo into an electric motor by supplying it with a current through the brushes, and, conversely, it is also possible to change any electric motor into a dynamo by supplying it with mechanical energy through the shaft.

54. Counter-Electromotive Force.—As soon as a motor-armature begins to rotate, it tends to act as if belonging to a dynamo, and begins to create an E. M. F. in opposition to that which sends a current through the brushes. This E. M. F. is called a *counter* E. M. F., and it is clear that the E. M. F. applied to the terminals must be equal to the counter E. M. F. plus the fall of potential in the armature.

55. Uses of Dynamos and Motors.—Dynamos are not used as frequently in electrotherapeutics as voltaic batteries, the latter being more convenient when only small units of electric energy are required. Sometimes, when larger volumes of current are needed, and electric circuits used for city lighting are at hand, these circuits may be utilized for operating an electric motor, while the latter again may furnish the necessary power for running a small dynamo. The high voltage of the lighting mains, which usually is either 110 or 220 volts pressure, may in this manner be changed into a voltage sufficiently low to be used in connection with an electric cautery.

56. As there are dynamos that produce continuous, and others that produce alternating, electromotive forces, so there are motors capable of using either of these electromotive forces, though, as a rule, a motor built for one of these varieties of E. M. F. is unable to be run by the other. It is also to be noticed that a motor is designed for a special speed and

E. M. F., and, when these conditions are fulfilled, it is showing its highest efficiency. If compelled to run at other speeds or with higher or lower electromotive forces than those for which it was intended, it is likely to run at a certain disadvantage, and be unable to utilize as much of the power supplied as it otherwise would. A motor may also be operated by means of a storage or a primary battery, and in any of these cases its speed is regulated by means of a suitable rheostat.

57. Sinusoidal Alternator.—A peculiar form of alternator is the *sinusoidal alternator*, constructed by A. E. Kennelly;

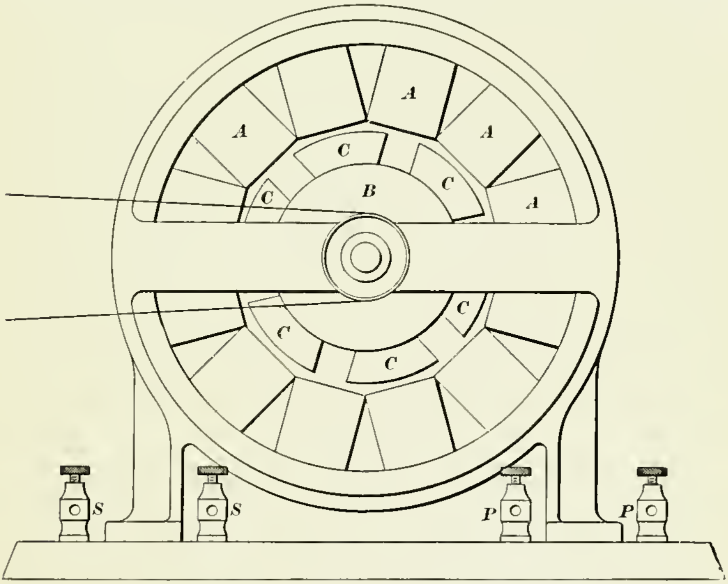

Fig. 37.

it is intended to furnish sinusoidal alternating currents, and is shown in Fig. 37. Here *A*, *A* are spools with two separate coils, an inner one with eight layers of fine wire and an outer one with two layers of coarse wire.

The inner coils are all connected in series and constitute the secondary coil, while the outer coils are connected in another series and form the primary coil of the machine. The primary coils are connected with the binding-posts *P*, *P*, from which

they receive a continuous current. The posts *S*, *S* receive the sinusoidal current furnished by the secondary coils, and deliver it from there by means of conducting-wires to the desired points. *B* is the armature, which is provided with a pulley, by means of which it may be operated by a small motor. *C*, *C* are teeth projecting from the armature. Both the field-frame, cores, and armature are made up of laminated iron.

If, now, the primary coils have a current circulating through them, they will magnetize the cores of the spools *A*, *A*. The magnetic lines of force thus produced remain stationary in the cores as long as the armature is stationary, but, as soon as the latter begins to rotate, the lines of force will shift from one side of the spools to the other, and will cut the wires in the secondary coils first from one and then from the other side. It is clear, from what has already been said about induction, that an alternating E. M. F. must be produced in the secondary coils, and that, by giving suitable proportions to the projections on the armature surface, the resulting-current-waves may be made sinusoidal. At the speed of 4,800 revolutions per minute, the machine will deliver a current having 1,920 alternations per second.

TRANSFORMERS.

58. Construction.—We have already studied another source of alternating electromotive forces—the induction-coil; in that case the primary coil was operated by means of a primary battery. There is yet another source of a similar nature that should be mentioned, and that is the apparatus called a *transformer*. After what has previously been said about the induction-coil, the transformers should require very little additional explanation. The difference between the two is mainly in the operation of the primary coil; while the latter, in the induction-coil, is acted on by a pulsating and intermittent E. M. F., caused by the spring-contact; the primary coil of the transformer is furnished directly with an alternating E. M. F. from an electric-lighting station. A transformer needs, therefore, no moving parts whatever, and there is this

additional distinction between them: whereas the induction-coil is provided only with an *interior* core of iron, and the magnetic flux, therefore, has to return through the air, the transformer, on the other hand, is provided also with an *external* casing of laminated iron, thus permitting the magnetic flux to flow entirely through iron, or nearly so.

59. A view of one form of a transformer is given in Fig. 38. C is the iron core, which, as shown, entirely encloses the coils. It will be seen that there are four coils represented. Of these, P, P_1 form the primary, the two coils being connected in series, as indicated by conductor n. The terminals of the primary are shown at t and t_1. S, S_1 are two secondary coils, which, being exactly alike, may be connected either in series or in parallel, as desired, the terminals of the secondary a, b, c, d being brought out separately for this purpose.

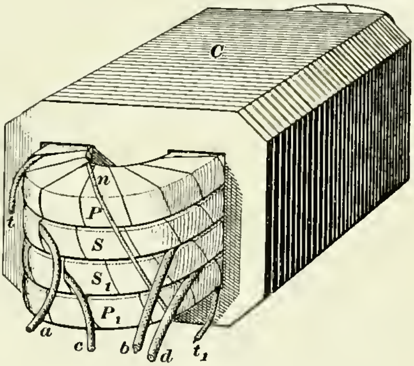

FIG. 38.

60. Use of Transformers.—While the main purpose of the induction-coil was to change a rather large current of low E. M. F. into a small current of high E. M. F., the transformer will not only do this, but will also change a current of high into one of low E. M. F. Transformers of the first kind are called *step-up transformers*, and when reducing the E. M. F., *step-down transformers.* The ratio of the secondary E. M. F. to the impressed E. M. F. is very nearly the same as the ratio of the number of turns in the coils. This ratio is called the *ratio of transformation.*

For ordinary applications, such as for lighting, step-down transformers are used, the usual ratio of transformation being 10 : 1, so that, with a 1,000-volt primary, the secondary E. M. F. is 100 volts.

The sizes of the primary and the secondary coils, shown in

Fig. 38, are very nearly equal, although the number of turns of the one is perhaps ten times that of the other. The size of the wire used in the secondary coil of this step-down transformer, however, must be so much larger in diameter than that of the primary that the volume of the two coils will be nearly the same.

61. The possibility, by means of transformers, of increasing or reducing the E. M. F. of a current, is of great advantage when it is desired to send electric energy to distances far away. It has been shown previously that an electric current will lose part of its E. M. F. in passing through a conductor. This loss amounts to a certain fraction of the total power furnished to the circuit, and may be expressed in watts. The amount in watts is found by multiplying the loss in E. M. F. by the current-strength; therefore, loss in watts, $W = E \times C$, or, $W = C \times R \times C$, because $E = C \times R$; W is, then, $C^2 \times R$.

We see from this that the loss is proportional to the product of C squared and R. It is therefore seen at once that it is of advantage to make C as small as possible, and this can only be done by increasing the E. M. F., as the product of C and E must remain the same, if the same power is to be furnished to the circuit.

It is therefore obvious that the higher the E. M. F., the smaller is the loss in the circuit for the same amount of power transmitted. If this is so, it would appear as a matter of course that the E. M. F. of the current should be raised to a very high value, but there are certain reasons why this is not so simple as it appears at first glance. For one thing, there is a certain pressure, beyond which it is not advisable to expose the alternator itself, and which it also would be dangerous to give to a current that has to enter private dwellings. It is here that the transformer is of advantage, and that it may be utilized in the following manner: An alternator in the electric-lighting station is delivering a current of suitable pressure to a step-up transformer in which the pressure of the current is increased and its amperage reduced. This current of high voltage is now sent through a well-insulated conductor to any desired point,

where it again enters a transformer, now a step-down transformer. In the latter, the amperage is again increased and its pressure reduced to a voltage low enough to enter a house without exposing the occupants to any unnecessary risks.

62. Transformers are also made especially for therapeutic purposes, so made that they can be connected with the lighting circuits of the building, and be able to furnish a strong current for cautery-work. They resemble an induction-coil somewhat, but are in reality step-down transformers, in which the current from the lighting circuit enters the primary coil and induces a low E. M. F. in a secondary coil made up of thick wire. The latter will then deliver a current of from 5 to 30 amperes, depending on the position of the secondary coil, whether situated near the end of the primary coil or at the middle.

63. Adapters.—A somewhat similar apparatus has also been made for the utilization of continuous currents. Its purpose is to make the installation of primary batteries superfluous, and to utilize the current from the lighting circuit for all the various therapeutic treatments. Instruments of this class are called *adapters.* As the pressure in the lighting circuits is either 110 or 220 volts, the adapter requires a rheostat to reduce the current to a voltage devoid of any danger to the patient, and various arrangements have been made so as to make it impossible for the operator to make a mistake and send a current through the patient that would either cause a direct injury, or indirectly so by submitting him to a nervous shock.

The adapter is usually provided with a milliammeter and an induction-coil operated in the ordinary way, by means of a continuous current and a vibrator. The rheostat is so arranged that the current, in passing in and out of the latter, has to pass through an incandescent lamp of 110 volts. There are, therefore, always two lamps in series with the rheostat, with a combined resistance of about 335 ohms, and the result is that, even with the whole resistance of the rheostat thrown off, the current would not exceed .3 ampere on a 100-volt circuit.

ELECTROMOTIVE FORCE AND DIFFERENCE OF POTENTIAL.

POTENTIAL.

64. When the *volt* and *electric pressure* were explained in Art. 4, *Direct Currents*, the terms *electromotive force*, *potential*, *difference of potential*, and *pressure* were given as identical and synonymous. This statement is not strictly correct; but it would have been useless at that point to have attempted a closer definition of these terms. It is after the student has considered the action of voltaic batteries that he is first able to fully understand the distinction between electromotive force and difference of potential, which we now will attempt to make clear.

65. Potential Energy and Potential.—If a weight is lifted above the ground to a height of, say, 10 feet, a certain amount of work is done and the weight is in position to do some work in return, either by driving a clock or some other apparatus. The weight in its new position has had imparted to it what is termed *potential energy*—that is, "ability to do work." The weight may already in its original position have been in possession of some potential energy, but by being raised to its present position its potential energy has been increased. In the following explanations we will, in place of the term "potential energy," simply use the word *potential.*

66. Thus, the water in a tank resting on the ground is in possession of a certain potential. By lifting the tank to the fourth floor of a house, neither the tank nor the water in it has undergone any change, but the *potential* of the water has been increased. Thus, by connecting it with a tube to a motor in the cellar, it will be able to perform a quantity of work that it previously was unable to do.

67. Difference of Potential.—If two tanks *A* and *B*, Fig. 39, are placed on the ground and filled with water to the

same level, there will be the same pressure per square inch at the bottom of either tank; and, if connection is made between them by means of the tube *C*, there will be no tendency of the water to flow into either of the tanks. But if the tank *A* is raised above the tank *B* there will be an excess of pressure on one side, and the water will flow into *B*. We see, then, that it is necessary to

FIG. 39.

establish a difference of pressure before a current of water will flow, as has been shown already in Art. **4**, *Direct Currents*. The tank *A*, being lifted to a greater height than *B*, is of a higher potential than *B*, and is, therefore, able to do more work than *B*. We come, then, to the conclusion that it is in reality the *difference of potential* between the two tanks that is the cause of the current of water flowing into *B*. This force, which tends to move the water through the tube when a *difference of potential* is established, we will call the *watermotive force*.

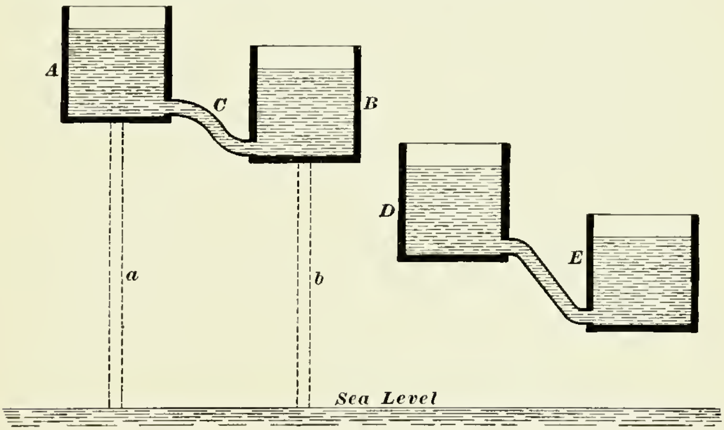

FIG. 40.

68. If, now, the tanks occupy a position relative to each other as indicated in Fig. 40, there is a difference of potential between them. We will say that this amounts to 3 pounds per square inch, and that the tanks are situated at a certain distance

above the sea-level, as shown in the figure. It is evident that no matter how high above or how deep below the sea-level these tanks may be placed, the difference of potential will remain the same, but that the potential of either will be increased by raising them above other tanks that may be situated in their vicinity. For instance, the tanks *D* and *E*, Fig. 40, may have the same difference of potential as *A* and *B*, yet it is clear that a connection between *B* and *D* will cause water to flow into *D* from *B*, instead of into the latter.

69. Zero-Level.—Evidently, then, the position of the tanks relative to other tanks must be considered, and some fixed point or line selected, in order that the distance above or below this line can be defined. For this purpose the sea-level has been selected, and by considering it to be a zero-line, it is possible to give the potential of either of these tanks relative to the sea-level.

70. If the tanks *A* and *B* are provided with two tubes *a* and *b* extended down to the sea-level, there will be a certain pressure at the base of either tube. Let, for instance, the level of the water in the tank *A* be 41.5 feet above the sea-level, and that in *B* 34.5 feet; then the pressure at the lower end of the tube *a* will be 18 pounds per square inch, and that of *b* 15 pounds. The difference of potential is still 3 pounds, but the potential of the water in the tanks *A* and *B* will be higher than that in *D* and *E*.

71. Positive and Negative Potential.—Should the tanks *A* and *B* be placed below sea-level, their difference of potential would still remain the same, but in the latter case water would flow through the tubes *a* and *b* into the tanks. In this case the water may be said to possess *negative* potential; it would, then, be of a *positive* potential if situated above sea-level.

We see from this that it is not necessary, when a difference of potential exists between two quantities of water, that the *lower* potential shall be *negative;* they may, in fact, *both* be negative or *both* positive.

72. Fig. 41 gives an illustration of two quantities of water, of which one, *A*, is of positive, and the other, *B*, of negative, potential. The sum of the two potential differences, in reference to the sea-level (here the zero-line) gives the total potential difference. Thus, if that of *A* is 5 pounds and that of *B* 3 pounds, the potential difference between *A* and *B* is 8 pounds.

73. Electric Potential.—When we apply these principles to *electric* potentials we arrive at the same results. Beginning again with Fig. 39, let us take a parallel case in electricity. If

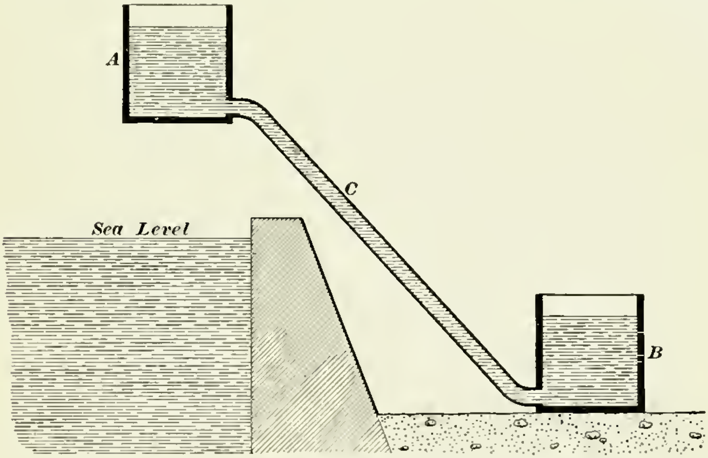

FIG. 41.

two conducting bodies are provided with quantities of electricity of the same potential or pressure, and they are brought into communication by means of a conductor, no current will flow.

ELECTROMOTIVE FORCE.

74. If the potential is increased on one of the bodies, a *difference of potential* will be established and a current will flow from the body of higher to that of lower potential, as was shown in Fig. 40. The force that moves the electricity from one body to another, when a difference of potential is established, is called *electromotive force.* The magnitude of the

E. M. F. depends, in this instance, on the difference of potential between the two bodies, and is expressed in *volts*. We will assume that this electric pressure amounts to 3 volts.

75. Zero Potential.—It is again evident that this pressure gives no idea of the potential on either of the two bodies; that, in fact, both may be possessed of a very high or a very low potential; or, that one of the bodies may be in an entirely neutral condition and possess no potential whatever. We come, therefore, to the same conclusion that we reached regarding the water-tanks, that it is necessary to select some arbitrary *potential level* to measure from. For this purpose the *earth* has been selected, it being assumed that its potential is zero. The earth is in reality of a negative potential, but this does not affect its function as a standard potential level, any more than the

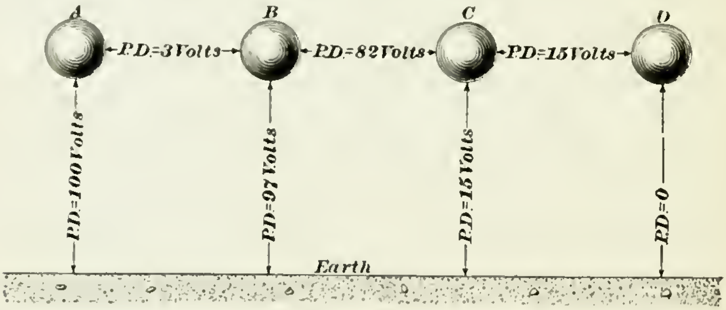

FIG. 42.

arbitrarily selected zero-point of a thermometer affects comparisons of temperatures.

Having a body of zero potential, so situated that it is accessible everywhere, it is now possible to compare the potential of any electrically-charged body with that of the earth, by means of suitable instruments, such as electrometers, galvanometers, voltmeters, etc. In either case, the potential difference between the charged body and the earth is found; but, as the earth is supposed to be at zero potential, the difference of potential will in reality show the electric potential of said body.

76. Electric Difference of Potential.—In Fig. 42 the four bodies *A*, *B*, *C*, *D* are supposed to have various potential differences (abbreviated to P. D.) relative to one another or to the earth, as indicated by the figures given. We see that the P. D. between *A* and *B* is 3 volts and between *C* and *D* 15 volts. Though the P. D. between the latter two bodies is greater, the P. D. between *B* and *C* is such that electricity would flow from *B* to *C*; in fact, we find between the latter bodies a P. D. as high as 82 volts.

77. Positive and Negative Potential.—The potentials indicated in Fig. 42 are all *positive*, because *above* zero, and there-

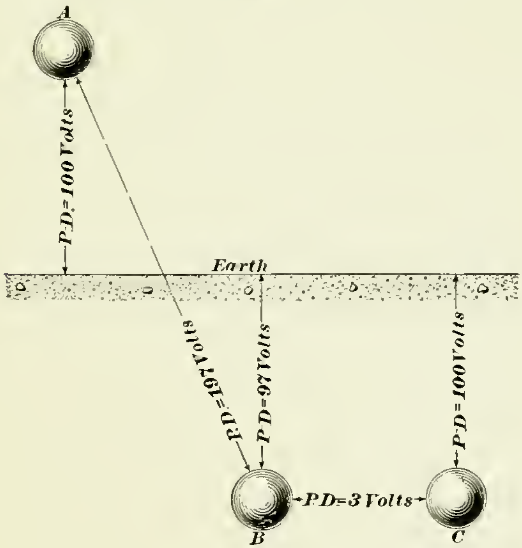

FIG. 43.

fore electricity will flow from them to earth. If their potentials are such that electricity will flow from earth to them, their potentials must be of values below that of the earth, and they are said to be of *negative* potentials.

78. It is often supposed that one of the bodies must be of a negative potential, in order to have a potential difference. We see in Fig. 42 that this is not necessary; that, in fact, both may

be positive or both negative and still have a P. D. The P. D. that exists when one body is of a positive and the other of a negative potential is seen in Fig. 43. Here the body *A* of Fig. 42 has retained its potential of 100 volts, while *B* has received a negative potential of 97 volts. The result is that the P. D. between them has increased to 197 volts, instead of to 3 volts. If compared with the body *C*, of 100 volts negative potential, the P. D. between the two would be 3 volts ; that is, electricity would flow from *B* to *C*.

79. Potential no Indication of Quantity.—It should here be added that, when speaking of a potential difference between two tanks of water at different levels, or two charges of electricity of different pressures, we know nothing about the quantity of water in either tank, or the amount of electricity on either body. The difference of potential gives no indication of quantity—simply of pressure. The P. D. between the Atlantic Ocean and a small bucket of water is not affected by the size of the former. Neither does the enormous size of the earth as compared with that of an electroscope affect the indications of the latter.

80. Fall of Potential.—In our considerations of batteries and the flow of the current in an external circuit, we found

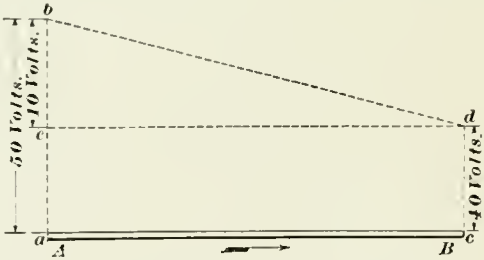

Fig. 44.

between any two points in the latter a certain potential difference. This latter may be termed the *fall* of potential between these points, and is identical with the E. M. F. required to send the current from one of the points to the other. For instance, in Fig. 44 we have part of a circuit *A B*, in which the potential at *a* is *a b* = 50 volts and at *c*, *c d* = 40 volts. The P. D. is

therefore 10 volts, and represents the loss of potential by the current in passing from a to c, or the E. M. F. required to send the current from a to c.

81. Distinction Between E. M. F. and P. D.—The terms E. M. F. and P. D. are in this instance virtually identical. Potential difference is in reality the amount of pressure or E. M. F. expended on that part of a circuit situated between any two points *external* to the *source* of the E. M. F. To say that the potential difference between any two points in an external circuit is the cause of the E. M. F. there expended, is not correct. The potential difference is, on the contrary, caused by the E. M. F. lost between the two points, and is proportional to this loss.

82. To speak of the *potential difference* of a battery on short circuit, or of a battery inclusive of an external circuit, meaning thereby the total E. M. F. of the battery, is entirely incorrect and very misleading. The fact is that nowhere in the circuit can two points be found where the difference of potential equals the E. M. F. of the battery. Indeed, it will be proved that a current can flow without an existing difference of potential, but never without an E. M. F.

Take, for instance, a battery of 6 cells, each cell of 1.1 volts E. M. F. and .1 ohm internal resistance. The total E. M. F. of the battery, if placed in series, is $6 \times 1.1 = 6.6$ volts, and the total resistance is $6 \times .1 = .6$ ohm. The current that this battery will deliver, if placed on short circuit, is, as found by Ohm's law, $C = \frac{E}{r'} = \frac{6.6}{.6} = 11$ amperes. The E. M. F. lost in the battery is $E = r' \times C = .6\,(\text{ohm}) \times 11\,(\text{amperes}) = 6.6$ volts; that is, the whole E. M. F. of the battery is lost in sending the current through it. What is now the potential difference between its terminals? Evidently there is none; they are both at the same potential.

Let, now, an external resistance of 5 ohms be added to the battery. We have, then,

$$C = \frac{E}{r' + R} = \frac{6.6}{.6 + 5} = \frac{6.6}{5.6} = 1.18 \text{ amperes.}$$

The volts lost in the battery are $r' \times C = .6 \times 1.18 = .708$ volt; therefore, the available E. M. F. = 5.89 volts. The highest difference of potential it is possible to find in the circuit is therefore 5.89 volts, which is considerably lower than 6.6 volts, the E. M. F. of the battery. The use of the term "difference of potential" must consequently be limited to that part of the circuit which is external to the source of the E. M. F.

83. There is one more reason for this limitation. It is always stated that in a circuit the current flows from the point of higher to that of lower potential. It is clear that this

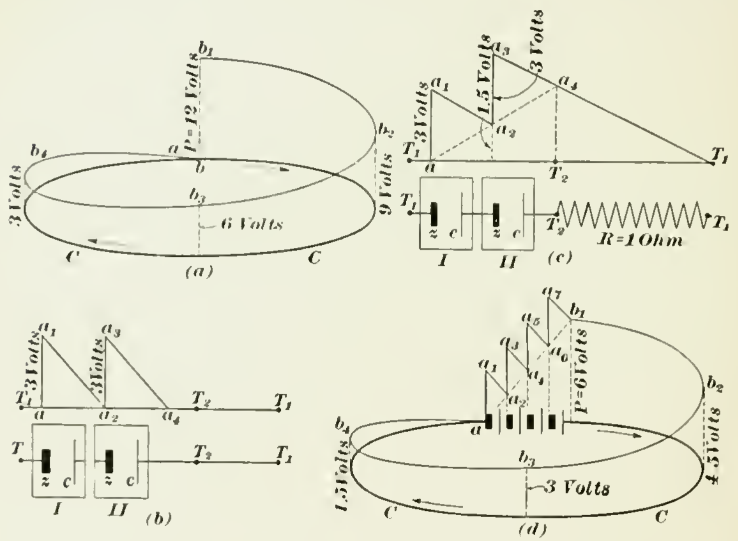

FIG. 45

rule cannot be applied to the flow of an electric current through the source of its E. M. F., such as a battery of galvanic cells, or the armature of a dynamo, as here the current flows from the point of *lowest* to to that of *highest* potential.

84. If an electric current did not lose any of its E. M. F. in passing through the source of the latter, and if, further, the current, in passing through this source, did not flow from a lower towards a higher potential, the conditions existing in an electric circuit might be somewhat like those indicated in

Fig. 45 (a). Here we have at b the source of the E. M. F., a sudden rise of electric potential from zero to, say, 12 volts, as shown by means of the curve $b_1\,b_2\,b_3\,b_4\,b$. From here the current, in passing along the conductor C in the direction of the arrow, gradually suffers a loss of potential, as indicated by the heights of the ordinates at the points b_1, b_2, b_3, until finally at b the potential falls to zero.

We will select two points a and b, very close together, and find their potential difference by passing from b to a in an opposite direction to that of the current, as shown by the arrows in Fig. 45 (a). Being very close together, their P. D. will be so small that it is negligible. If we now pass from a around the whole circuit to b, their P. D. will be equal to the total E. M. F. of the circuit. The same would be the case if any other two points in the circuit were chosen; the sum of the potential differences would equal the total P. D. In this instance the terms *difference of potential* and *electromotive force* would be interchangeable throughout the circuit; but the conditions are such as are not to be found in reality.

85. Cells on Short Circuit.—Let us now see what the conditions in the circuit, as far as the battery is concerned, really are, taking again as an example the case of a battery on short circuit. It is customary to say that the E. M. F. of the whole battery is equal to that of one cell multiplied by the number of cells. In Fig. 45 (b) there are two cells placed in series, each of, say, 3 volts E. M. F. and .5 ohm internal resistance; multiplying the 3 volts by 2, the number of cells, we have 6 volts as the total E. M. F. of the battery. We would now expect to find somewhere in the circuit a pressure of 6 volts, corresponding to this total pressure, but a closer investigation will reveal the fact that it does not exist, though as a matter of convenience we use this pressure in our calculations. The upper part of the figure will show the reasons for this. Here we have a diagram in which the line $T_1\,T_2$ represents zero pressure, and the ordinates the pressure at the corresponding points in the cells below. Beginning with the terminal T_1, which connects with the zinc z in cell I, we see that the current

in leaving the zinc immediately receives the whole E. M. F. of the cell, viz., 3 volts, as shown by the line $a\,a_1$. While the current is passing through the cell, it spends its pressure in heat, and arrives, therefore, at the zinc of cell *I* at zero potential, indicated by line $a_1 a_2$. This procedure is now repeated in cell *II*, and the action of this cell is shown by lines $a_2 a_3$ and $a_3 a_4$; the current arrives, then, at terminal T_2 again at zero potential, and passes through the short conductor $T_2\,T_1$, which is supposed to connect the two terminals, and back to the first cell. Notwithstanding the fact that our calculation tells us the total E. M. F. is 6 volts, we fail to find such pressure at any place in the circuit; in fact, the diagram shows that at no point does the E. M. F rise above that of *one* cell. Of course, a summing-up of the volts lost in each cell, multiplied by the number of cells, will give us the total E. M. F. as calculated.

86. Cells Combined With External Resistance. In Fig. 45 (*c*) the same cells are used in connection with an external resistance *R* of 1 ohm. The total E. M. F. is still the same, 6 volts, but the current-strength is reduced to 3 amperes. It has already been shown how to calculate the loss in a cell, and it will therefore be sufficient to simply say that in this instance the loss of pressure is current $\times$ resistance $= 3 \times .5 = 1.5$ volts per cell. Following the path of the current in Fig. 45 (*c*) we again find that its pressure, at the zinc of cell *I*, rises to 3 volts; but, as now only one-half of the current is flowing, the loss in the cell is only one-half of the total, or 1.5 volts. The current then arrives at the zinc in cell *II* with this pressure, and has another 3 volts added, making the total pressure at this point 4.5 volts. Again, 1.5 volts are lost in cell *II*, and the current finally arrives at the terminal T_2 with a pressure of $4.5 - 1.5 = 3$ volts. These volts are lost in passing through the resistance *R*, so that at terminal T_1 the current is again at zero potential. The variations of pressure are shown diagrammatically by the lines $a\,a_1$, $a_2 a_3$, $a_4\,T_1$ in the figure, and the dotted line $a\,a_2\,a_4$ indicates the average increase in E. M. F. Again, we fail to find a total E. M. F. of 6 volts, though in this instance the maximum pressure is $3 + 1.5 = 4.5$ volts, and

therefore higher than in the first instance. We come, then, to the conclusion that an increase in the external resistance will bring the pressure in the cells higher and higher, until when the resistance has reached its maximum—that is, when the circuit is open—the E. M. F. also has reached its full value. In the present instance this would amount to 6 volts.

87. After having seen the changes that take place in the E. M. F. of a current, while passing through the source of said E. M. F., we are now able to represent the circuit shown in Fig. 45 (d) as it in reality would be if 4 cells, each of 3 volts E. M. F. and .5 ohm resistance, were placed in series. They would have the total E. M. F. of 12 volts shown in Fig. 45 (a).

Beginning at point a, we have a repetition of the phenomenon illustrated by means of Fig. 45 (b) and (c); that is, the E. M. F. suddenly rises, then falls again, while passing through each cell, until when point b_1 is reached we have a pressure of 9 instead of 12 volts. The maximum pressure would in this instance be found at a_7, where it is $6 + 1.5 = 7.5$ volts, while the average rise in pressure is indicated by the dotted line $a\, a_2\, a_4\, a_6\, b_1$.

It will not now require much of an explanation to show that nowhere in this circuit can a P. D. of 12 volts be found, and the figure clearly shows the limitations of the term *difference of potential.*

THE HYDRO-ELECTRIC BATH.

RESISTANCE OF THE BATH.

88. Resistance of Water.—When a patient is placed in an electric bath for the purpose of having an electric current sent through his body, it is important to so arrange matters that as great a part of the current as possible will pass through the body, instead of uselessly wasting its energy by traversing the water. It is also of value to know how much of the electric current flows through the patient's body, as a whole, and how much through its various parts, and also to see how the position

of the body in the bath affects the current distribution between the body and the water.

This subject seems, in general, to be little understood, and it will therefore be the aim, by means of various diagrams, to make it more comprehensible. We will first consider the bath alone, without any foreign body in it. Let *A*, in Fig. 46, be a tank made of glass plates of the dimensions given in the drawing

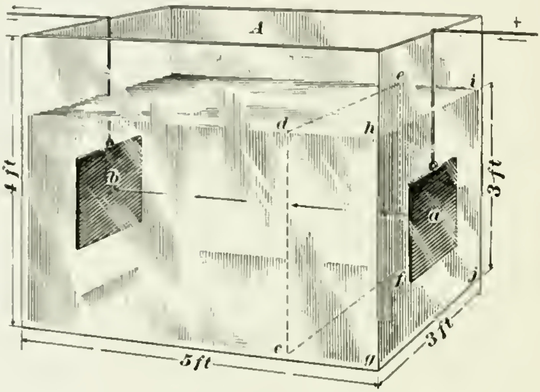

FIG. 46.

and filled with water to the height of 3 feet. The current passes through the bath from the anode a to the cathode b, as indicated by the arrows. So far we have nothing but a simple fluid conductor, and, from what has already been said in Arts. **11**, **12**, and **13**, *Direct Currents*, it should be easy to find the resistance of the bath. Assuming that the resistance of the water is 10 ohms per cubic foot, we find the total resistance in the following manner: The sectional area of the water is 3 ft. $\times$ 3 ft. $=$ 9 square feet.

Let $r_1 =$ specific resistance per cubic foot;
$r_2 =$ required resistance;
$a_1 =$ 1 square foot;
$a_2 =$ sectional area of the bath.

Then, since the resistance varies inversely as the sectional area,

$$r_1 : r_2 :: a_2 : a_1, \text{ or } r_2 = \frac{r_1 a_1}{a_2}.$$

In the present instance, $r_1 = 10$, $a_1 = 1$, and $a_2 = 9$; therefore,

$$r_2 = \frac{10 \times 1}{9} = \frac{10}{9} \text{ ohms.}$$

This means that a column of water having a sectional area of 9 square feet and *a length of 1 foot* has a resistance of $\frac{10}{9}$ ohms. In the figure, this column is indicated by the letters *c d e f g h i j*.

The resistance of a given conductor increases as the length of the conductor increases; it follows, therefore, that the resistance of the *whole* bath is found by multiplying the resistance of 1 foot, as found above, by the total number of feet. Calling the whole length L, we find the total resistance

$$r_2 = \frac{10}{9} \times L = \frac{10}{9} \times 5 = 5.5 \text{ ohms.}$$

The total resistance of all the water may, therefore, be found by the following formula:

$$r_2 = \frac{r_1 a_1}{a_2} \times L.$$

As a_1 in this formula stands for 1 square foot, and therefore does not affect the equation, it can be omitted. The formula will then read

$$r_2 = \frac{r_1 \times L}{a_2}.$$

This formula will be used throughout this Paper in this form, and may be expressed in words as follows: *The total resistance of the fluid in a bath is found by multiplying the specific resistance of the fluid per cubic foot by the length of the bath in feet, and dividing the product by the cross-sectional area of the bath in square feet.*

EXAMPLE.—A water-tank 4 feet high, 3 feet wide, and 6 feet long is filled with water to a height of 3 feet. The resistance of the water is 15 ohms per cubic foot; what is the resistance of the water in a longitudinal direction?

SOLUTION.— $r_1 = 15$ ohms, $a_2 = 3 \text{ ft.} \times 3 \text{ ft.} = 9$ square feet, and $L = 6$ feet. Therefore, using formula $r_2 = \frac{r_1 \times L}{a_2}$, we have

$$r_2 = \frac{15 \times 6}{9} = \frac{90}{9} = 10 \text{ ohms. Ans.}$$

EXAMPLE.—Find the resistance of the water in the last example, if one-half has been removed.

SOLUTION.— $r_1 = 15$ ohms, $a_2 = 3 \times 1.5 = 4.5$ square feet, and $L = 6$ feet. Therefore,

$$r_2 = \frac{15 \times 6}{4.5} = 20 \text{ ohms. Ans.}$$

EFFECT OF INSERTION OF A SOLID BODY.

89. Solid Body of Known Dimensions.—Let us now introduce a solid substance into the water and study the effect it may have on the total resistance. In Fig. 47, B is a block

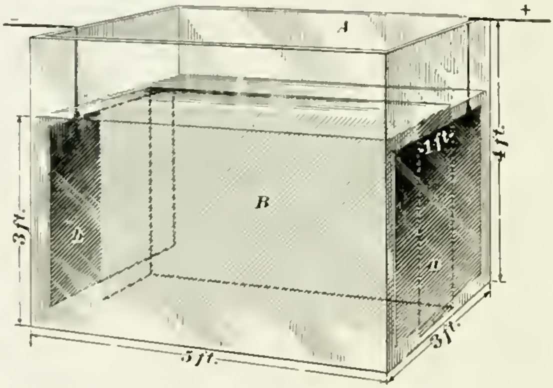

FIG. 47.

made of a material similar in resistance to that of the human body. The dimensions of the tank remain as before, and as indicated in the figure. The block B is 5 feet long, 3 feet high, and 1 foot wide; its resistance is 5 ohms per cubic foot. The anode a and cathode b are supposed to be wide enough to send the current simultaneously through both the block and the water on either side of the former, the resistance of the water to be 10 ohms per cubic foot.

The resistance of the block and the water is now found in a manner similar to that shown in the previous example. Let us first consider the block. From the formula

$$r_2 = \frac{r_1 \times L}{a_2}$$

we find its resistance to be

$$r_2 = \frac{5 \times 5}{3} = 8.33 \text{ ohms.}$$

In the same manner, the resistance of the water is

$$r_2 = \frac{10 \times 5}{3 + 3} = \frac{50}{6} = 8.33 \text{ ohms.}$$

The sectional area of the water is taken as 6 square feet, because the block, being 1 foot wide only, a space 1 foot wide remains on each side, which, multiplied by the height of 3 feet, gives an area of 6 square feet.

90. The current in amperes that would flow through the water in the tank illustrated in Fig. 46 is found by a simple application of Ohm's law as follows: The E. M. F. is supposed to be 7 volts and the resistance was found to be 5.5 ohms; then,

$$C = \frac{E}{R} = \frac{7}{5.5} = 1.272 \text{ amperes.}$$

The conditions, as shown in Fig. 47, are somewhat different, as we have here *three* conductors in parallel, and the current from the anode a will therefore divide into three parts, one flowing through the block and the others through the water on either side. The latter two branches may be combined as one, and was so considered in the calculations. The two branches of water may be considered as one, because we may imagine the block to stand against one of the walls with all the water on one side. In that case the total cross-sectional area of the water will be double that of either of the branches, and will have only half the resistance of either.

In order to make a distinction between the resistance of the block and of the water, that of the former will be designated by R_2, while that of the water remains r_2 as before. The joint resistance of the two may be found by means of the formula for derived circuits given in Art. **113**, *Direct Currents*. Let R stand for the joint resistance, then

$$R = \frac{R_2 \times r_2}{R_2 + r_2} = \frac{8.33 \times 8.33}{8.33 + 8.33} = \frac{69.39}{17.66} = 4.165 \text{ ohms.}$$

Utilizing the same voltage as before, the amperage now would be

$$\frac{E}{R} = \frac{7}{4.165} = 1.68 \text{ amperes.}$$

91. We will now proceed a step further and find the joint resistance of a block, standing isolated, as in Fig. 48, and surrounded by water. The dimensions of the tank remain as before, while the block is now only 3 feet long, 3 feet high, and 1 foot wide. Considering the resistance of the water in sections, we have first the column *c d e f g h i j*. Leaving the resistance of

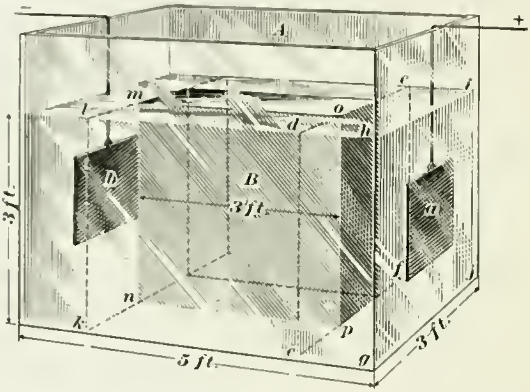

FIG. 48.

the water at 10 ohms per cubic foot, we find the resistance of the said column

$$r_2 = \frac{r_1 \times L}{a_2} = \frac{10 \times 1}{9} = 1.11 \text{ ohms.}$$

There is a similar column at the other end of the block; the resistance of both in series will be $2 \times 1.11 = 2.22$ ohms.

Next we come to the column *c d o p k l m n* on one side of the block. Its resistance is

$$r_2 = \frac{10 \times 3}{3} = 10 \text{ ohms.}$$

As there is a similar column on the other side with the same resistance, their joint resistance will be $\frac{10}{2} = 5$ ohms.

The resistance of the block B is $R_2 = \dfrac{5 \times 3}{3} = 5$ ohms.

This block, in conjunction with the water on each side, forms two parallel branches; their joint resistance is therefore again found by means of the formula for joint resistanees, that is,

$$\frac{R_2 \times r_2}{R_2 + r_2} = \frac{5 \times 5}{5 + 5} = \frac{25}{10} = 2.5 \text{ ohms.}$$

We now have the total resistanee of the whole tank, inelusive of the block, as follows:

		Ohms.
(a)	The eolumn $c\,d\,e\,f\,g\,h\,i\,j$ . . .	1.11
(b)	Joint resistance of block B and water, each side	2.50
(c)	Another eolumn, similar to that of (a)	1.11
	Total resistance R	4.72

Again, using an E. M. F. of 7 volts, the eurrent-strength would be

$$\frac{E}{R} = \frac{7}{4.72} = 1.483 \text{ amperes.}$$

Comparing the eurrents flowing in the tanks, illustrated by means of Figs. 46, 47, and 48, we find them to be, respectively, 1.272, 1.68, and 1.483 amperes. As was expected, the total resistance of the water in Fig. 46 was lowered by inserting the block of lower specific resistance, as shown in Fig. 47. Fig. 48 may be considered a combination of the two.

Referring again to Fig. 48, it is obvious that the conditions would be unaltered if the bloek were laid flat on the bottom of the tank; the seetional area and the length of the path offered the eurrent would be the same as before. It would in that position more nearly eompare with the lower extremities of a person sitting in the bath.

92. The conditions, however, would be entirely different if the block were plaeed upright, in the position shown in Fig. 49. Retaining the same dimensions of the tank and bloek as before, we see that the block will occupy the whole width of the tank. The resistance of the water in either end of the tank is found in the same manner as before,

$$r_2 = \frac{r_1 \times L}{a_2} = \frac{10 \times 2}{9} = \frac{20}{9} = 2.22 \text{ ohms.}$$

This resistance, added to that of the water at the other end, makes the total resistance of the water 4.44 ohms. The resistance of block B is

$$R_2 = \frac{r_1 \times L}{a_2} = \frac{5 \times 1}{9} = \frac{5}{9} = .55 \text{ ohm.}$$

Therefore, the resistance of the whole is $4.44 + .55 = 4.99$ ohms.

We see that, while the resistance of the block in Fig. 48 was 5.0 ohms, in the position shown by Fig. 49 it is only .55 ohm; but the resistance of the water is so much higher in proportion

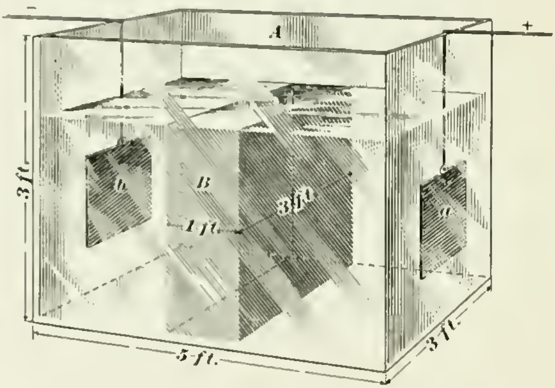

FIG. 49.

that the total resistances in the two examples are very nearly the same. The current-strength in the arrangement shown in Fig. 49, if we still retain the pressure of 7 volts, is

$$\frac{E}{R} = \frac{7}{4.99} = 1.42 \text{ amperes,}$$

while the current in the case illustrated in Fig. 48 was 1.483 amperes.

93. But (and here comes the important question) how much of the current does the *block* receive while placed in either of the two positions? As the block, in these examples, is supposed to represent the whole or part of the human body,

it is necessary to fully understand how the position of the block affects the amount of current it will receive.

In Fig. 49 the amperage was 1.42 and the block evidently receives the whole of the current, as it is the only path the current can take in passing from one end of the tank to the other.

Let us now see how much current the block receives if placed as in Fig. 48. There the block had a resistance of 5 ohms, and the water on either side a joint resistance of 5 ohms; the current will therefore divide into two equal parts and the block will receive one-half of the total, or $\frac{1.483}{2} = .742$ ampere.

If these results are placed together in a tabular form, we shall be able to compare them more easily.

Bath.	Total Resistance of Block and Water. Ohms.	Resistance of Water Alone. Ohms.	Resistance of Block Alone. Ohms.	Total Current Through Bath. Amperes.	Current Through Block. Amperes.
Fig. 48	4.72	7.22	5.00	1.483	.742
Fig. 49	4.99	4.44	.55	1.42	1.42

94. We see from this that the *number of amperes passing through the bath is not an indication of the current-strength through the block*, as the total amperage in the first instance is greater than that in the second, and, notwithstanding this, it receives only one-half the current given to the block in the latter instance.

95. Current Distribution in a Block.—It has, so far, been shown that the position of the block determines the current-strength that flows through it as a whole. We will next see how some parts of a block can receive a stronger current than others. This part of the subject bears more directly on the actual conditions prevailing when a patient is sitting in an electric bath. At first glance it would seem probable that every part of the human body submerged in the bath would be pervaded by the same number of amperes, independently of how

the body might be situated, whether placed horizontally or vertically. But a closer consideration of the subject will show that this is not the case; that the parts placed vertically will receive a heavier current than if placed horizontally, and also the sectional area of the various parts will determine how large a fraction of the whole current they will receive.

In Fig. 50 we have a block consisting of a vertical part *B* and a horizontal part *C*. The dimensions of the tank and the block

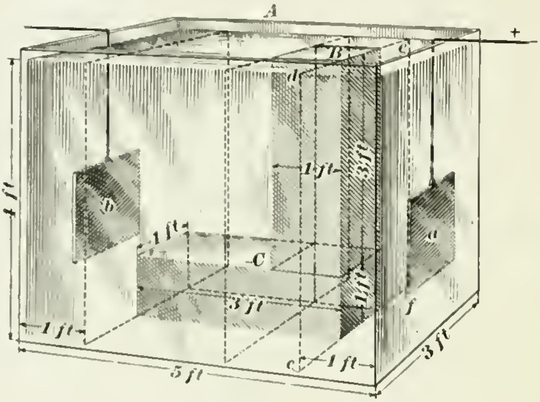

FIG. 50.

are indicated in the figure. Proceeding in the same manner as already shown—that is, by dividing the figure in smaller parts and considering each separately—we find that the resistance of *B* is 1.66 ohms, of *C* 15 ohms, and of the entire contents of the tank, 3.86 ohms. Taking a pressure of 7 volts, the total current-strength will be,

$$\frac{E}{R} = \frac{7}{3.86} = 1.81 \text{ ampere,}$$

which will be apportioned as follows:

Vertical part *B* will receive	.481 ampere.
Horizontal part *C* will receive	.266 ampere.
Water on either side will receive . .	1.066 amperes.
Total	1.813 amperes.

This table informs us that the current-strength through the vertical part B is heavier than that through part C. Is the current-strength per square foot also greater? Considering the current per square foot of sectional area, we arrive at a different result; then, B has $\frac{.481}{3} = .16$ ampere per square foot, while C has $\frac{.266}{1} = .266$ ampere. This so-called *density* of the current will be explained further on.

96. To complete this part of the subject, there is yet to be considered the instance where the block is leaning towards

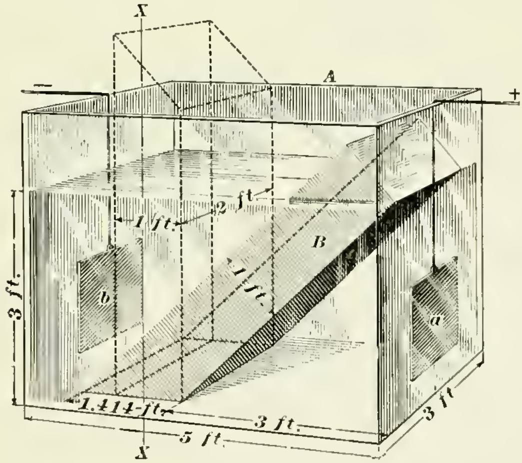

FIG. 51.

either the anode or the cathode. In Fig. 51, the block B is shown as leaning towards the former. In order to show the difference caused by this inclination, the block is first placed in a vertical position, as indicated by dotted lines, and the total resistance of the bath, and that of the block alone, found. The total resistance of the block and the bath together is 5.11 ohms; of the block, .833 ohm; and of the water adjoining the block on each side, 3.33 ohms. Fig. 52 is a sectional elevation of Fig. 51, taken along the line $x\,x$, and shows the position of the block relative to the water on each side. The joint resistance of the two columns of water c, c was shown above to be 3.33 ohms.

The current passing through the bath will now distribute itself inversely as the resistance of the block and the water at that place. To find these subdivisions of the current, we will first have to determine the total current-strength. If we assume the pressure to be 7 volts, then Ohm's formula makes

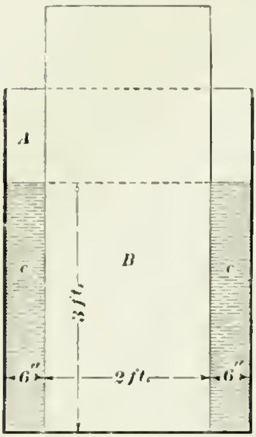

Fig. 52.

$$C = \frac{E}{R} = \frac{7}{5.11} = 1.37 \text{ amperes.}$$

That part of the current which passes through the block may be called c_1, and is found from the following proportion :

$$.833 : 3.33 :: (1.37 - c_1) : c_1,$$

which gives c_1 the value of 1.095 amperes, and therefore the current through the water is

$$1.37 - c_1 = 1.37 - 1.095 = .275 \text{ ampere.}$$

Next, the block B is turned upside down, so as to rest with its inclined base on the bottom of the tank, as B in Fig. 51. If the inclination of the block with the base is at an angle of 45°, as here shown, the length of the base will now be 1.414 feet, instead of 1 foot, as before. As the current travels from a to b it will have to traverse the block in a direction parallel with the base, therefore through a distance of 1.414 feet. It will therefore seem that in this position the block would receive a smaller current ; but the results, as formulated in the following table, show that the effect is different :

Resistance and Current.	Block in Upright Position.	Block Inclined at an Angle of 45°.
Total resistance of water and block	5.11 ohms	4.928 ohms
Resistance of block	.833 ohm	1.178 ohms
Resistance of water at side of block	3.33 ohms	4.713 ohms
Total current at a pressure of 7 volts	1.37 amperes	1.42 amperes
Current through water at side of block	.275 ampere	.284 ampere
Current through block	1.095 amperes	1.136 amperes

We notice that the resistance of the block indeed does increase by being tilted, but, as the block in this position displaces a greater amount of water than it did before, it follows, if we assume that the water is kept at the same level, that there is now less water in the tank than before. From the fact that the water had double the resistance of the block, it follows, also, that, if we replace a certain part of the water with a corresponding part of the block, the total resistance must decrease. This we find to be so; the total resistance has gone from 5.11 down to 4.928 ohms, and the total current has accordingly increased from 1.37 to 1.42 amperes.

The block, in either case, receives the same percentage of the total current. If, therefore, after tilting the block, the pressure is reduced to 6.75 volts, we find the conditions entirely unchanged.

97. Body of Unknown Dimensions.—So far we have dealt with known quantities; that is, we have dealt with blocks the specific resistance and dimensions of which were known; with columns of water of another specific resistance also known, and have attempted to find their joint resistances. We have also seen the various effects caused by altering the positions and dimensions of the blocks so far as these effects related to the total resistance and current-distribution in the bath. We are now prepared to go further, and find the resistance of bodies whose dimensions and specific resistances are unknown. These problems lead up to the conditions that actually prevail when the human body is submerged in a bath. We have to determine the dimensions and specific resistance of this body, in order to know how the electric current really distributes itself in the bath—that is, how much goes through the body and how much through the water.

98. In Fig. 53 there is shown a tank *A*, with the dimensions there indicated, which is filled to a height of 2 feet with water. The specific resistance of the water is, as before, 10 ohms per cubic foot. Letting r_2 again stand for the unknown resistance

of the water, we find its value by means of the formula already used, viz.,

$$r_2 = \frac{r_1 \times L}{a_2}.$$

where r_1 = specific resistance ;
a_2 = sectional area ;
L = the length.

Then,

$$r_2 = \frac{r_1 \times L}{a_2} = \frac{10 \times 5}{6} = \frac{50}{6} = 8.33 \text{ ohms.}$$

Now let a block B be placed in the tank, when the water rises to a height of 3 feet. The dimensions and specific resist-

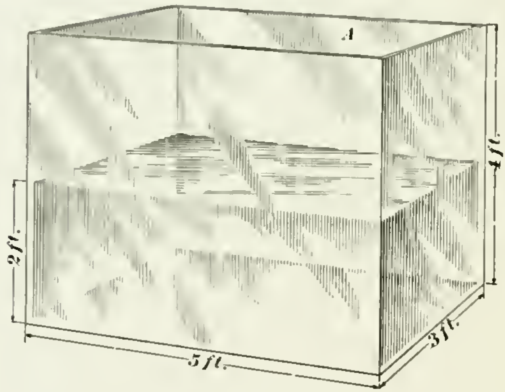

Fig. 53.

ance of this block are unknown, and it is required to find its resistance in ohms.

The method to pursue in this case is the same as the method by which the joint resistance of two conductors was found. In Art. **113**, *Direct Currents*, it was stated that, if two conductors a and b were placed in parallel, their joint resistance R could be found by the following formula :

$$R = \frac{a \times b}{a + b}.$$

If R is known, and either of the other factors is unknown, they can be found by means of the same formula after properly transposing it, as follows :

$$(a+b)R = a \times b\,;$$
$$aR + bR = a \times b\,;$$
$$bR = a \times b - aR\,;$$
$$bR = a(b - R)\,;$$

$$a = \frac{b - R}{bR}, \text{ or } b = \frac{aR}{a - R}.$$

If $r_2 =$ resistance of the water alone ;
$R_2 =$ resistance of the block ;
$R =$ joint resistance of both ;

the formula will assume the following form :

$$R_2 = \frac{r_2 \times R}{r_2 - R}.$$

If both r_2 and R_2 are known, then their joint resistance is found as follows :

$$R = \frac{r_2 \times R_2}{r_2 + R_2}.$$

The resistance of the water alone was already found to be 8.33 ohms, and the block has been inserted in the water for the purpose of finding the joint resistance of water and block. The conditions will now be as indicated in Fig. 55, where there is a column of water A and a block B, both placed in parallel ; a current is sent from the conductor a through both and into the conductor b.

By actual test the joint resistance was found to be 4.165 ohms. It is now desired to find the resistance R_2 of the block. From the formula

$$R = \frac{r_2 \times R}{r_2 - R}.$$

we find

$$R_2 = \frac{8.33 \times 4.165}{8.33 - 4.165} = \frac{34.69}{4.165} = 8.33 \text{ ohms.}$$

That this answer is correct can be proved directly by taking the dimensions, as given in the drawing, and calculating the resistance of the block after the manner already shown. Taking the formula

$$r_2 = \frac{r_1 \times L}{a_2}$$

we have as before

$$r_2 = \frac{5 \times 5}{3} = \frac{25}{3} = 8.33 \text{ ohms.}$$

99. It is important to have it clearly understood *how* the resistance of the block *B* was found, and *why* it is thus found, as this problem has been considered from a different point of view, and calculations made, which place the resistance of the immersed body far too high.

It will be remembered that, in order to find the resistance of *B* in Fig. 54, the joint resistance of the block and water was

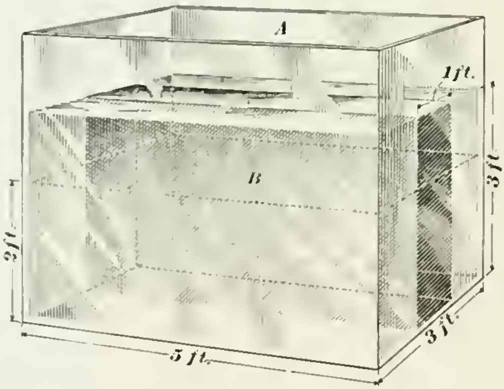

FIG. 54.

found, and also the resistance of the water alone. Before the insertion of the block, the water was at a height of 2 feet; after the block was inserted, the water rose to a height of 3 feet. It must be borne in mind that at no time was any water *added* or *removed;* the conditions remained entirely unaltered during both tests.

100. The other and incorrect method of finding the resistance of the block is as follows: At first the conditions are

exactly as represented in Figs. 53 and 54; that is. the tank A is filled to a height of 2 feet with water, then the block is inserted, and the water, of course, again rises to a height of 3 feet. The joint resistance of the water and block is now found, and is, as before, 4.165 ohms. The block is again removed and the level of the water falls back again to 2 feet. Instead of now measuring the resistance of *this* quantity of water, the joint resistance of which, with that of the block, was just found, it was thought that the proper conditions would not prevail unless the water was brought up again to the level that it occupied while the block was inserted. Enough water was therefore poured in to bring the water from the height of 2 feet up to that of 3 feet.

Evidently the conditions have now been altered, and when the resistance of this increased quantity of water is found it will

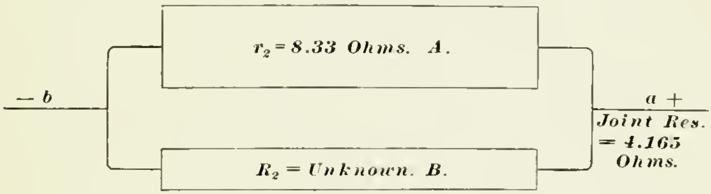

FIG. 55.

no longer be the resistance of the water placed in parallel with the block, but something else. Fig. 56 will show the conditions now existing, as compared with those previously shown in Fig. 55. The only factor remaining the same is the quantity of water marked A, whose resistance was found to be 8.33 ohms. The joint resistance of the additional water C and the quantity A is 5.55 ohms, and it is now desired to find the resistance of the block.

We proceed, then, as shown in the previous instance, and use the formula

$$R_2 = \frac{r_2 \times R}{r_2 - R};$$

r_2 is now 5.55 ohms and R = 4.165 ohms, as before. The formula will therefore read:

$$R_2 = \frac{5.55 \times 4.165}{5.55 - 4.165} = 16.65 \text{ ohms}.$$

Here, then, we have an answer that makes the resistance twice that previously found. It is clear that this must be the result, for the following reasons: When the joint resistance of the 2 feet of water and the block was found, it was observed that each of them contributed a certain portion toward the total resistance, and thus, by finding the resistance of one, that of the other could be found. But instead of taking the water as it was, some more water was added to it, thereby decreasing its resistance; in fact, the latter fell from 8.33 down to 5.55 ohms. It must now be evident that, when the resistance of the block is deducted from the total resistance, the block has a greater resistance placed to its credit than it deserves, so that, instead of having a resistance of 8.33 ohms, it is now credited with an increased resistance of 16.65 ohms.

Fig. 56 is the same as Fig. 55, except for the additional quantity of water marked *C*. In Fig. 55 the joint resistance of *A*

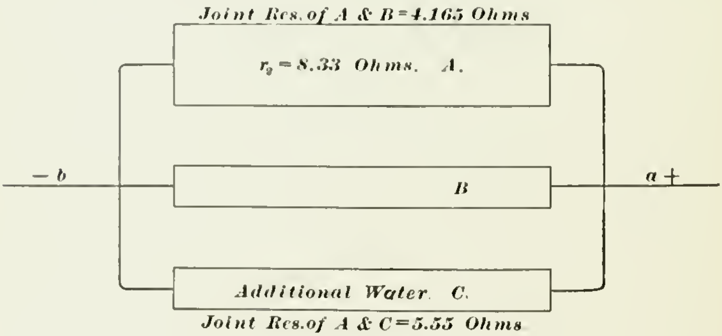

FIG. 56.

and *B* was found, and then that of *A*. By means of these factors that of *B* was found. In Fig. 56 the joint resistance of *A* and *B* was first found, and then the joint resistance of *A* and *C*, instead of *A* alone, and from these joint resistances that of *B* was supposed to be found. What, in reality, was done was to find the joint resistance of *A* and *C*, and then to find some other body, which, if placed in parallel with *A* and *C*, would give a total resistance of 4.165 ohms.

101. To still further show the difference between these two methods of measuring the resistance of the submerged body, we will take an actual case in which a patient was placed in a bath tub of the dimensions given in Fig. 57. The tub was first filled to a height of 17 inches with water and then the body was

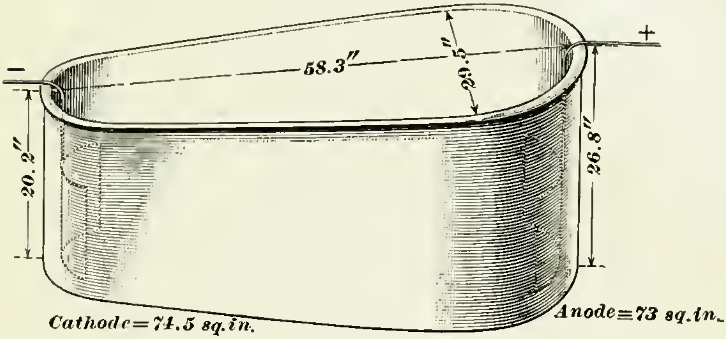

FIG. 57.

placed in it. Of course, the level of the water was now higher, but the water was allowed to drain off until the former level of 17 inches was again restored. Now the joint resistance of body and water was measured and found to be 77.5 ohms. After removing the body, the water-level sank below the 17 inches it first occupied, but no water was added, and the resistance, when measured, was found to be 103.8 ohms. By means of the formula previously used, viz.,

$$R_2 = \frac{r_2 \times R}{r_2 - R},$$

we find the resistance of the body

$$R_2 = \frac{103.8 \times 77.5}{103.8 - 77.5} = 306 \text{ ohms.}$$

This was the method followed out and illustrated by means of Fig. 55.

Calculating the resistance of the body according to the method shown in Art. **98**, we have the following: To begin with, the water was at a height of 17 inches, as before, and after inserting

the body the level was again reduced to 17 inches, when the joint resistance was measured and found to be 77.5 ohms. Instead of measuring the resistance of the water remaining when the body was removed, a new quantity of water was added, until the height was again 17 inches. The resistance of the water was now found to be 91 ohms, which value was inserted in the formula instead of 103.8, and the formula then appears as follows:

$$R_2 = \frac{91 \times 77.5}{91 - 77.5} = 552 \text{ ohms.}$$

This resistance is 522 — 306 = 216 ohms larger than the one previously found.

In these tests the temperature of the water was 98° F., and the current 89 milliamperes.

102. Other experiments have shown that a lowering of the water-level causes an increase in the total resistance of the bath, as was to be expected. While the length of the resisting medium remains the same, the sectional area is constantly decreasing, causing an increase in resistance. If the current of 89 milliamperes is to be maintained, it will require a constantly increasing voltage.

The following table will clearly show the relations between height of water, resistance, and voltage:

Height of Water. Inches.	E. M. F. Volts.	Joint Resistance of Body and Water. Ohms.	Resistance of Water Alone. Ohms.	Resistance of Body. Ohms.
17	6.9	77.5	103.8	306
15	7.8	87.6	115.4	364
13	8.9	100.0	127.7	461
11	10.2	114.6	140.4	623

CURRENT-DENSITY IN THE HUMAN BODY.

103. Influence of Depth of Water.—It will be of importance to ascertain what proportion of the total current passes through the body, and how the height of the water influences the current-distribution. Looking at the first line

of the last table, we find the resistance of the water to be 103.8, and that of the body 306, ohms. That proportion of the total current of 89 milliamperes which either of them is able to transmit, will therefore be inversely proportional to their resistances, and may be found by means of the following proportion :

$$103.8 : 306 :: x : (89 - x);$$

in which x stands for the current going through the body, and $(89 - x)$ for the remainder, which passes through the water. We find the current through the body to be 22.54 milliamperes, and that through the water, 66.46 milliamperes. The body will therefore conduct 25.3 per cent. of the total current, while the remainder, or 74.7 per cent., is uselessly passing through the water.

If the height of the water is *reduced*, the body is receiving still *less* current, as will be seen from the table below.

Height of Water. Inches.	Proportion of Total Current Passing Through Body. Per Cent.	Proportion of Total Current Lost in the Water. Per Cent.
17	25.3	74.7
15	24.04	75.96
13	21.7	78.3
11	18.4	81.6

104. Current-Density in Body.—In glancing at this table, and seeing that, with the water at a height of 17 inches, the body receives a current 25.3 per cent. of the total, it must not for a moment be supposed that the *whole* body is traversed by a uniform current of this proportion. On the contrary, it simply means that the *average* current amounts to this much ; at some points it will be stronger, at others weaker. The reason for this was plainly shown in describing Fig. 50 ; but the deductions there made may here be applied to the special case of the human body. Let, for instance, a person, while sitting upright in the bath, occupy with the *trunk* of his body

one-half of the total width of the tub at that point. With a current-strength of 89 milliamperes the *trunk* should, under the circumstances, be traversed by a current of 44.5 milliamperes, if body and water were of the same specific resistance; but it was shown that the body had only $\frac{1}{2}$ the resistance of the water; the water will therefore get $\frac{1}{3}$ only of the total current, and thus the body receives a current of 59 milliamperes, amounting to 66.3 per cent., instead of the 22.5 milliamperes it was supposed to receive.

Again, take the body at its lower extremities, for instance near the ankles; here the sectional area of the latter, relative to that of the water at that point, may be $\frac{1}{50}$ only. The ankles should therefore, by reason of their higher conductivity, receive $\frac{2}{50}$, or 4 per cent., of the total current, which in this instance would amount to 3.56 milliamperes only.

105. It is clear, then, that, even after the total current-strength has been determined, the amount of current that various parts of the body may receive is still dependent on other conditions. It shows, in fact, that it is possible with a current of moderate strength to give some parts of the body a current of greater strength. This explains why, in some cases, certain parts of the skin are reddened out of all proportion to the amount of current they are supposed to receive. It shows that the current *density* at some points is far beyond the average density.

106. Density.—By current *density* is meant the current-strength per unit of cross-sectional area of a conductor. In the present case, the square foot may be taken as the unit of area. We see, then, that the density must vary *directly* with the current-strength, and *inversely* with the area of the transverse section. That is, if the total strength of the current is constant, an increase in sectional area of the conductor will decrease the density of the current per unit area.

If D stands for density of current, C for current-strength, and A for the sectional area, then $D = \frac{C}{A}$.

As an example, let us take the block in Fig. 50. The total current-strength was here found to be 1.813 amperes; of this B received .481 ampere, C, .266 ampere, and the water on the side of the block, 1.066 amperes. The current-density in either of these parts is found by the formula $D = \frac{C}{A}$; therefore, the value of D for the part B is $\frac{.481}{3} = .160$ ampere, for C it is $\frac{.266}{1} = .266$ ampere, and for the water $\frac{1.066}{6} = .178$ ampere.

107. While speaking of density, it may here be of interest to mention a peculiar variety of the electric bath. It was shown that 75 per cent. of the current is lost by passing outside the body. To avoid this, it has been suggested to place a diaphragm across the bath and let the human body project through the former. The current will then, at the point where the diaphragm is situated, pass wholly through the body, because it is unable to pass through the diaphragm. That the latter will increase the total resistance of the bath is one thing; but another and more serious consequence is that the current at this particular section is concentrated to a very high degree—in other words, is of great density, perhaps dangerously so.

CONSTRUCTION OF THE BATH.

108. Material of Bath-Tub.—It is important that the tub itself is not a conductor of electricity, otherwise the whole current would circulate around the water without entering the latter at all. Even a metal bath-tub covered with an insulating coating is to be avoided, as sooner or later some parts of the coating will wear or break off, and then the current will be able to make a short circuit through the metal wall. Oak or porcelain are the most suitable materials for its manufacture, the latter being the more cleanly of the two.

109. Importance of Insulation.—Insulation is an important point that needs careful attention—particularly, if

the current from the lighting circuits is to be utilized. It is therefore evident that the water in the tub must not be directly connected with the waste- or water-pipe, as either of these communicates with the ground; the current would, if the anode be near the waste-pipe, go mostly into the ground, and a small portion only into the bath. In case the current is supplied from some lighting mains, the patient might be subject to most dangerous short circuits. Therefore the necessity of having the tub entirely disconnected both from the waste-pipe and from the water-supply pipes.

110. Dimensions of the Bath-Tub.—In Fig. 57 the more important dimensions of a bath have already been shown, and Fig. 58 gives, by means of a sectional elevation, some further details needed for a clear understanding of its construction. The latter figure is a sectional elevation of a wooden

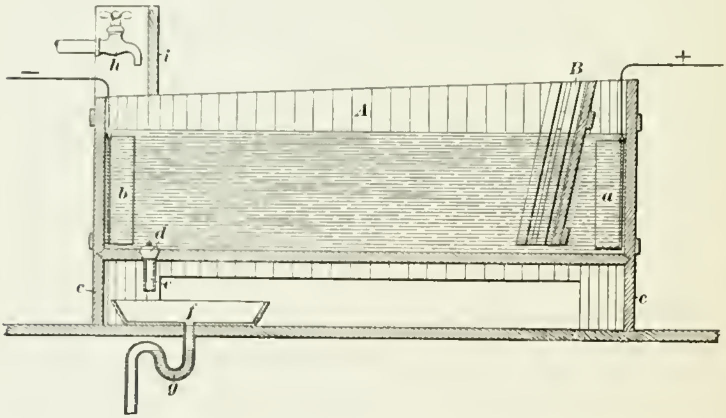

FIG. 58.

tub partly filled with water. *A* is the tub itself, and *B* a back rest to prevent a direct contact with the anode *a*; the cathode *b* is unprotected. The stopper is marked *d* and is inserted in the upper part of the short outlet-tube *e*; consequently, there is no direct connection with the sewer-pipe *g*. The pipe *e* conducts the water into a shallow basin *f*, from which it flows into the pipe *g*. To give room and access to the basin *f* and also to

give free circulation of air under the tub, the latter is supported by legs *c*, *c*. Around the supply-pipe *h* is built some kind of a guard *i*, to prevent a direct contact with the tube *h* on the part of the patient ; otherwise, he might, under certain conditions, be exposed to a short circuit.

MONOPOLAR AND DIPOLAR BATHS.

111. Dipolar Bath.—A bath may be *monopolar*, *dipolar*, or *multipolar*. So far, the baths considered have been of the dipolar order, and to this class the multipolar baths may also be said to belong, as a multiplication of poles simply means a subdividing of the anode and cathode.

112. Monopolar Bath.—By *monopolar* bath is not meant a bath with one active pole only, but rather a bath that contains only one electrode submerged in the water while the other is exterior to same. The bath-water is therefore of one polarity, either positive or negative, and may be considered as an electrode that completely envelops the body and thus provides a very large surface contact.

113. Difference Between Monopolar and Dipolar Baths.—There is quite a difference between a monopolar and a dipolar bath. A current is passing through the latter, of which the body receives a certain portion, depending on its position and size, some parts receiving more than others ; how much, as has been shown, is not always easy to tell.

In the monopolar bath, the conditions are entirely changed. Here the exterior electrode, for instance, the anode, is placed in contact with the body at any desirable point, and at this point the current is compelled to enter—here *only*, and what is more, the *whole* current. There is, then, no longer any uncertainty of where the current acts and in what strength. In leaving the body again, the current is diffused over a very large area ; in fact, over the whole submerged part of the body.

The monopolar bath may therefore localize the action of the current to one particular spot, if desirable ; while the dipolar

bath gives a general distribution of electricity through the whole body. The exterior pole, in a monopolar bath, may consist of a metal rod, covered with wash-leather and placed across the widest part of the bath. This rod is connected, by a well-insulated wire, to one of the terminals of the electric source, and, when the patient grasps the rod in his hands, the current will pass through his arms and trunk to the water.

114. Paddle Electrode.—If it is desirable to localize the action of the current to one particular spot, a so-called "paddle" electrode is used. This consists of a metal electrode whose dimensions are about 5 in. × 7 in., and which is provided with a long handle of insulating material. The operator can, by means of this "paddle" electrode, concentrate the action of the current on any desirable part of the body, either by holding the electrode stationary against the part in question, or by imparting to the electrode a circulating motion, if it is desirable to affect a larger area.

115. Other Electrodes.—In the *multipolar* bath there is, besides the electrodes at head and foot of the bath, also a "lumbar" electrode, usually 6 in. × 10 in. By means of these three electrodes, various combinations may be made. For instance, the lumbar may work in conjunction with the "head," or, as is usually called, the "cervical," electrode, and the "foot" electrode. Or, the cervical may be placed opposite the lumbar electrode and both be acting as "lateral" electrodes. If the foot terminal is removed and the lateral electrodes are of opposite polarity, the current will travel across the bath only, and act on the special organs situated in its path.

A further variation may be made by covering the "lumbar" electrode with a light wooden framework and utilizing it as a "gluteal" electrode. By letting the patient sit on this and use it in conjunction with the cervical and foot terminals, or with the latter alone, a further localization of the current may be accomplished.

It should be remembered that the quantity of current which the body will receive, also depends on its proximity to the

electrodes, so that this provides a further means for giving a local as well as a general application of the electric current.

116. Stationary and Movable Electrodes.—The various electrodes used in a multipolar bath may be either *stationary* or *movable*. In the former instance, the walls of the bath are usually perforated and the insulated wires passed through these openings. The conducting wires all lead to a common switchboard, where, by means of plugs, any electrode may be thrown in or out of action. This arrangement of stationary electrodes has certain advantages from the fact that the electrodes are always ready for action and need no additional handling. At the same time, there are certain drawbacks inherent in the system. For one thing, the arrangement is less flexible than with movable electrodes, unless their number is increased; then again, the perforation of the sides of the bath leads sooner or later to a leakage. But the greatest disadvantage results from the numerous electrodes constantly situated in the bath, some of which at times are idle and, as such, cause complications that it is difficult to avoid. A special instance will make this clearer.

117. Suppose that in Fig. 50 two lateral electrodes are placed parallel with and opposite to the block *B*, and that the resistance of the block and water at this point is 20 ohms. The lateral electrodes are supposed to be out of action; but we find on closer examination that they, in reality, are interfering with the intended action of the current. If the joint resistance of the two lateral electrodes is .5 ohm, it is clear that the current will follow the paths of least resistance, and pass through *them*, instead of through the water and the block. In other words, the electrodes serve to short-circuit the water and block at this point, preventing either of them from receiving the current intended for them.

For these reasons it is preferable to have removable electrodes and to have these supported by means of stout, well-insulated wires, which pass over the edge of the bath instead of through the walls.

The electrodes are made of bright metal, covered, if necessary, with a light lattice-formed frame of wood, which can be removed when the electrodes need cleaning. Their dimensions may be as follows: cervical electrode, 11 in. × 11¼ in.; lumbar electrode, 6 in. × 10 in.; and the foot electrode, 8½ in. × 14¾ in.

ELECTRIC CURRENTS USED AND THEIR REGULATION.

118. Direct and Alternating Currents.—The electric current in nearly all its varieties is used for hydro-electrical purposes. We have first the ordinary *direct* current, as furnished by a voltaic battery or by the lighting stations; then the *pulsatory* current, as determined by a dynamo with few coils. The *alternating* currents of an induction-coil, of a sinusoidal alternator, or of a transformer fed from some lighting circuit are employed. It will be unnecessary to here again make a distinction between these various forms of electric currents, as this has been fully done in the part headed, "Constant and Variable Electromotive Forces."

119. If the direct current is to be supplied by means of voltaic cells, it is of importance that the latter are of good size, so as to be of sufficient capacity and to be able to run for long periods without removal. How to select the proper number of cells and connect them has already been fully explained. As for the regulation of the current, this may be accomplished either by means of a rheostat, so made as not to heat, or by means of a double-handed cell-selector. The latter is perhaps the preferable of the two, as it is not liable to overheat itself; this may happen to the rheostat, if not so made that it is able to control a current of a strength up to 300 milliamperes. The rheostat, or cell-selector, should of course be so constructed that the current can be entirely shut off.

120. Measuring Instruments.—A further requirement is a *milliammeter* that will register the current up to 300 milliamperes. Sometimes a *voltmeter* is also useful for measuring the voltage of the battery or for testing separate cells. As a rule,

the milliammeter is so made that, by the addition of a suitable resistance, it may be changed into a voltmeter.

121. Current From Lighting Circuits.—When the direct current is taken from the lighting circuit, the bath must, as has already been said, be well insulated. In addition to disconnecting the bath from the waste- and supply-pipes, it should be placed, either on vulcanized-rubber blocks or on glass insulators of the mushroom variety, which may be filled with some heavy oil.

122. Current From Induction-Coils.—When the current from an *induction-coil* is used, the baths should have an interrupter with a smooth action, and the speed of the spring should be variable between wide limits, say between 1,000 and 4,000 interruptions per minute. An induction-coil that consists of a primary coil only has lately been used for the electric bath. It depends for its action on the self-induction alone, and belongs, therefore, strictly in the class of a direct-interrupted current, as the current does not change direction. Its self-induction is very high; the make-current is therefore very weak, while the break-current predominates to such an extent that it is really the only active one. Its regulation is accomplished by subdividing the coil and throwing part of it out of action, if the current-strength is to be reduced.

123. Current From Alternators.—The alternating current from the lighting circuits has been used quite extensively in operating transformers intended for the supply of a sinusoidal current. When alternating currents are so utilized, it is still more important to provide safety appliances for the prevention of accidents. Each of the primary conductors should therefore have an efficient magnetic cut-out. Even then it is a question whether it is not more advantageous to simply use the supply-current for operating a motor, and let the latter furnish the driving power for a sinusoidal alternator. It would give opportunity for not only more closely regulating the voltage and the frequency, but also for varying the wave form of the E. M. F., thus making the action either smooth or abrupt.

UNITS.

FUNDAMENTAL UNITS.

124. The units used in electricity and magnetism have partly been explained at various places in the Papers of this Course, but it is advisable to repeat the definitions already given and to add others not yet included, for the sake of easy reference, and in order to show more clearly the relation and derivation of the various units.

The units are divided into the following subdivisions: fundamental units, derived units, electrostatic units, magnetic units, electromagnetic units, and practical units.

The absolute and practical units are based upon the three *fundamental* units of *length*, *time*, and *mass*, which are defined as follows:

125. Unit of Length.—The *centimeter*, or the unit of *length*, represents $\frac{1}{1000000000}$ of the distance from the pole to the equator on the surface of the earth, and is equal to .3937 inch, or 1 inch equals 2.54 centimeters, nearly. A *square centimeter* is the area contained in a square, each of whose sides is 1 centimeter in length; 1 square centimeter equals .155 square inch, or 1 square inch equals 6.45 square centimeters, nearly. A *cubic centimeter* is the volume contained in a cube, each of whose edges is 1 centimeter in length; 1 cubic centimeter equals .06102 cubic inch, or 1 cubic inch equals 16.387 cubic centimeters.

126. Unit of Mass.—The *gram*, or the unit of *mass*, or *quantity*, of *matter*, represents the quantity of matter contained in a cubic centimeter of pure water at the temperature of its maximum density, which is 4° C., or 39.2° F., and is equal in weight to 15.432 grains.

127. Unit of Time.—The *second*, or the unit of *time*, represents $\frac{1}{86400}$ of a mean solar day.

128. Absolute, or C. G. S., Units.—The system of units derived from these are named the *absolute*, or *C. G. S.*,

system, to distinguish it from other systems based on other fundamental units.

129. Derived Units.—From these fundamental units the following secondary units are derived :

The *unit of velocity*, or the rate at which a body changes its relative position, is determined by dividing the distance in centimeters through which a body travels by the time in seconds required to travel that distance. The unit of velocity is, therefore, *1 centimeter per second.*

The *dyne*, or the unit of *force*, is that force which, by acting upon a mass of 1 gram for 1 second, can give to it a velocity of 1 centimeter per second.

The *erg*, or the unit of *work*, is the amount of work performed when a force of 1 dyne is overcome through a distance of 1 centimeter. It has already been stated that the *practical* unit of work in electrical measurements was the *joule;* 1 joule is equal to 10,000,000 ergs.

The *unit of power*, or the *rate of expending energy*, is *1 erg per second.* Consequently, as the *watt* is equal to *1 joule per second*, it must also equal 10,000,000 ergs per second.

130. Electrostatic Units.—The following units have no special names :

The unit *quantity* is a quantity of electricity which is able to repel another similar and equal quantity with a force of 1 dyne at a distance in air of 1 centimeter.

The unit *potential* is that potential which requires the expenditure of 1 erg of work to bring a unit quantity of electricity from zero potential to that potential.

The unit *electromotive force*, or *difference of potential*, exists between two points if a unit quantity of electricity will do 1 erg of work in passing from one point to the other.

The unit *current* is one which conveys a unit quantity of electricity through a conductor in 1 second.

The unit of *capacity* is possessed by a conductor if a charge of 1 unit of electricity brings it up to unit potential.

The unit *resistance* of a conductor is that which requires unit electromotive force to send a unit current through it.

131. Magnetic Units.—The unit *magnetic pole* is one of such strength that it, at a distance of 1 centimeter in air, repels a similar pole with a force of 1 dyne.

The *magnetic potential* at a point, due to a magnet, is the work required to remove a unit magnetic pole from that point, against the magnetic attraction, to an infinite distance. This work is measured in ergs.

The unit *difference of magnetic potential* exists between two points when it requires the expenditure of 1 erg of work to bring a (north or south) unit magnetic pole from one point to the other against the magnetic forces.

The *strength of a magnetic field* is measured by the force it exerts upon a unit magnetic pole; therefore, the unit *intensity of a magnetic field* is that which acts on a unit pole with a force of 1 dyne.

132. Electromagnetic Units.—The unit *strength of current* is one which in a wire of 1 centimeter length, bent so as to form an arc of a circle of 1 centimeter radius, exerts a force of 1 dyne on a unit magnetic pole placed at the center.

The unit *quantity of electricity* is the quantity which a unit current conveys in 1 second.

The unit *electromotive force*, or *difference of potential*, is that which must be maintained between two points on a conductor, in order that unit current may do 1 erg of work in 1 second.

The unit *resistance* of a conductor is that which permits a unit current to flow through it, when unit electromotive force is maintained between its ends.

The unit *capacity* of a condenser is that which a unit quantity of electricity will raise to unit potential.

PRACTICAL UNITS.

133. Index Figures.—Some of the absolute, or C. G. S., units would be either too large or too small for practical use. The following units, called *practical electric units*, have therefore been selected so as to be of a magnitude convenient for ordinary use. They are decimal multiples of the absolute units; but, as it would require numerous figures to express the value of the

practical units in absolute units, a system of writing has been adopted in which, by means of index figures, these large figures can be reduced to a number of few figures.

The index may either be *positive* or *negative*, and signifies in the first case the number of tens by which the figure is to be *multiplied*, and in the latter case the number of tens by which it is to be *divided*. For instance, $3 \times 10^2 = 3 \times 10 \times 10 = 3 \times 100 = 300$; $2 \times 10^3 = 2 \times 10 \times 10 \times 10 = 2{,}000$; $4 \times 10^6 = 4{,}000{,}000$. $3 \times 10^{-2} = \frac{3}{10 \times 10} = \frac{3}{100} = .03$; $4 \times 10^{-3} = \frac{4}{10 \times 10 \times 10} = \frac{4}{1000} = .004$; $2 \times 10^{-6} = \frac{2}{10^6} = \frac{2}{1000000} = .000002$; $\frac{1}{5} \times 10^3$ would be $\frac{1}{5} \times 1{,}000 = 200$, while $\frac{1}{5} \times 10^{-3}$ would equal $\frac{1}{5} \times \frac{1}{1000} = \frac{1}{5000} = .005$.

134. Unit of Current.—The *absolute electromagnetic* unit of current is too large for ordinary purposes, and the practical unit of current has therefore been reduced to one-tenth part of the former unit, and is then called *1 ampere*. An ampere is thus 10^{-1} of an absolute (electromagnetic) unit of current-strength.

A current of electricity, when passing through water, decomposes it into its two elements, *hydrogen* and *oxygen*. The quantity of water decomposed is proportional to the strength of the current flowing, and also to the time during which it flows. Consequently, a unit strength of current can be conveniently adopted by agreeing that it is that strength of current which will decompose a certain quantity of water in a certain time, and agreeing upon the quantity of water and the time.

By universal agreement, 1 ampere is that strength of current which will decompose .00009324 *gram*, or .0014388 *grain*, of water in 1 second. It will also in 1 hour deposit 4.024 grams, or 60.52 grains, of silver in a silver cell, which is at the rate of .001118 gram, or .01681 grain, of silver per second. This is almost exactly *1 grain of silver per minute*.

135. Unit of Electromotive Force.—The *absolute electromagnetic* unit of electromotive force is so small that it would take 100,000,000 of these units to express the E. M. F. of a single

Daniell's cell. When it comes to high E. M. F., the number would be enormous, and it has therefore been decided to take 100,000,000 (10^8) absolute units, and of these make a new unit, called *1 volt.*

It was stated in Art. **57**, *Magnetism and Electromagnetism*, that if a conductor, in passing through a magnetic field, cuts lines of force at the rate of *1 line of force per second*, 1 absolute unit of potential was generated. It follows, therefore, that to generate 1 volt the conductor must cut across 100,000,000 (10^8) magnetic lines of force per second. The E. M. F. of a Daniell's cell is about 1.1 volts.

136. Unit of Resistance.—The *practical* unit of resistance is 1,000,000,000 times as great as the absolute electromagnetic unit. The units of the volt and ampere determine the magnitude of this unit, as, according to Ohm's law,

$$1 \text{ unit of resistance} = \frac{1 \text{ unit of electromotive force}}{1 \text{ unit of current}};$$

but, as the practical unit of E. M. F. is 100,000,000 absolute units, and the practical unit of current is $\frac{1}{10}$ of the absolute unit, it follows that 1 practical unit of resistance $= \dfrac{100,000,000}{\frac{1}{10}}$ $=$ 1,000,000,000 (10^9) absolute electromagnetic units of resistance.

137. This practical unit of resistance has been named *1 ohm.* The *true* ohm is the resistance offered by a column of mercury 106.3 centimeters high and 1 square millimeter in sectional area at the freezing-point of water, or 0° C.

The *legal* ohm is the unit of resistance generally employed in technical measurements, although it is probably .3 per cent. smaller than the true ohm. One legal ohm is the resistance offered by a column of mercury 106 centimeters high and 1 square millimeter of sectional area at freezing-point of water, 0° C. The dimensions of the column, expressed in inches, are as follows: 41.7323 inches high and .00155 square inch of sectional area.

The resistance of 100 yards of ordinary iron telegraph-wire is about 1 ohm.

138. Unit of Quantity.—The practical unit of quantity is the *coulomb;* it is $\frac{1}{10}$ (10^{-1}) of the absolute unit of quantity of the electromagnetic system. It can deposit .001118 gram of silver.

139. Unit of Capacity.—The *farad* is the practical unit of capacity and is $\frac{1}{1000000000}$ (10^{-9}) of the absolute electromagnetic unit of capacity.

140. Unit of Power.—The *watt*, or volt-ampere, is the practical unit of power. It is obtained by multiplying together volts and amperes. One watt equals 1 joule per second, therefore .7374 foot-pounds per second, or $\frac{.7373}{550} = \frac{1}{746}$ of a horsepower. 1,000 watts equals 1 kilowatt.

141. One *watt-second* is 1 watt expended for 1 second. One *watt-hour* is the energy expended by 1 watt for 1 hour, or 2,654.4 foot-pounds.

One *kilowatt-hour* is the quantity of energy supplied in 1 hour by a current of such voltage that the product of volts, amperes, and hours comes to 1,000; for instance, a current of 5 amperes at 20 volts for 10 hours, or a current of 100 amperes at 10 volts for 1 hour.

142. Even these units are sometimes either too large or too small, and prefixes of *mega*, *micro*, and *milli* are then used. They facilitate the calculations and measurements of exceedingly large or small quantities.

Mega means "one million"; *micro*, "one-millionth part"; and *milli* "one-thousandth part."

For instance, 1 *microhm* is equal to $\frac{1}{1000000}$ of an ohm. Therefore, to express the resistance in microhms, multiply the resistance in ohms by 1,000,000; and, conversely, to express the resistance in ohms, divide the resistance in microhms by 1,000,000.

The *megohm* is a unit of resistance which is equal to 1,000,000 ohms, and is used chiefly to measure the resistance of bad conductors and insulators.

The *microfarad* is $\frac{1}{1000000}$ of a farad; a *milliampere* is the thousandth part of 1 ampere.

143. Ratio of the Electrostatic to the Electromagnetic Units.—The dimensions adopted for similar units in these two systems are not the same. It would go beyond the limits of this Paper to explain why this is so, and it must therefore suffice to simply call attention to the fact and point out how great the differences are.

The following table shows the ratio between the *practical*, the *electrostatic* (C. G. S.), and the *electromagnetic* (C. G. S.) units:

Characteristic.	Practical Units.	Electromagnetic (C. G. S.) Units.	Electrostatic (C. G. S.) Units.
Current-strength	1 ampere	10^{-1}	3×10^{9}
Quantity . .	1 coulomb	10^{-1}	3×10^{9}
Potential	1 volt	10^{8}	$\frac{1}{3} \times 10^{-2}$
Resistance	1 ohm	10^{9}	$\frac{1}{9} \times 10^{-11}$
Capacity	1 farad	10^{-9}	9×10^{11}

The ratio between the electromagnetic and the electrostatic units is therefore as follows:

Electromagnetic (C. G. S.) Units.		Electrostatic (C. G. S.) Units.
1 unit of current-strength	=	3×10^{10} units.
1 unit of quantity	=	3×10^{10} units.
1 unit of potential	=	$\frac{1}{3} \times 10^{-10}$ units.
1 unit of resistance	=	$\frac{1}{9} \times 10^{-20}$ units.
1 unit of capacity	=	9×10^{20} units.

We see from the first table that the practical unit, *ampere*, is $\frac{1}{10}$ of the electromagnetic (C. G. S.) unit of current-strength, and that the practical unit, *volt*, is equal to 100,000,000 electromagnetic (C. G. S.) units of potential. The practical unit, *ohm*, equals 1,000,000,000 electromagnetic (C. G. S.) units of resistance.

From the last table it is seen that the *electromagnetic* unit of quantity is 30,000,000,000 times greater than the corresponding *electrostatic* unit, while on the other hand the electrostatic unit of potential is 30,000,000,000 times greater than the *electromagnetic* unit of potential.

Direct Currents.

DIRECT CURRENTS.

(1) What can you say in regard to the statement often made that eleetrieity is a mystery?

(2) How do we recognize the presence of eleetricity?

(3) How does our knowledge of electrical phenomena eompare with our knowledge of the phenomena of gravitation?

(4) Are the laws upon which the science of electricity is based exact?

(5) Is it possible to make a study of eleetrieity without knowing the nature of electrieity?

(6) Why is the expression "producing" eleetrieity ineorrect?

(7) What do you understand by electrieity?

(8) Define eleetrification.

(9) Why must work be performed to eleetrify a substanee?

(10) What is the ether?

(11) Does ether possess inertia?

(12) What do you understand by inertia?

(13) What is the function of ether?

(14) Is the existenee of ether a mere supposition?

(15) How do you prove its existence?

(16) Is ether present in a vacuum? How is this proved?

(17) Where is the ether?

(18) How did the word eurrent eome to be applied to electricity and magnetism?

(19) Does electricity flow?

(20) If it does not flow, why is the term eurrent used?

(21) What causes water to flow from one place to another?

(22) What causes the electric current to flow from one point in the electric circuit to another point in the same circuit?

(23) Define electromotive force. What are the other terms often used instead of electromotive force?

(24) Is it correct to speak of producing an electromotive force?

(25) Is the presence of an electromotive force sufficient to obtain an electric current?

(26) What is a volt?

(27) What does E. M. F stand for?

(28) How many volts are required to overcome the affinity of oxygen for hydrogen?

(29) Define (*a*) the coulomb; (*b*) the ampere.

(30) State, in the form of an equation, the relation between the coulomb, ampere, and time in seconds.

(31) Is a coulombmeter of any service in electrotherapeutics?

(32) Has a coulomb any reference to time?

(33) What other words are used as synonyms for ampere?

(34) Explain the difference between current-tension and current-intensity.

(35) Explain briefly why a loss of pressure occurs when a current is flowing through a conductor.

(36) What do you understand by electrical resistance?

(37) What is (*a*) the ohm? (*b*) the microhm?

(38) How does the resistance of a metallic conductor vary with the temperature of the conductor?

(39) Upon what does the resistance of a conductor depend?

(40) What are the dimensions and temperature of a column of mercury, the resistance of which is 1 ohm, adopted as the unit of resistance by the Electrical Congress?

(41) If a copper conductor 100 feet in length and .2 square inch in cross-sectional area has a resistance of 5,000 microhms, what will be the resistance in ohms of the same conductor when its length is 1 mile?

(42) What will be the resistance in ohms of 100 feet of a copper conductor, the area of whose cross-section is .1 square inch?

(43) State Ohm's law.

(44) A difference of potential of 110 volts exists between the terminals of a conductor whose resistance is 20 ohms; find the current flowing through the circuit.

(45) A current of 10 amperes is flowing through a circuit whose resistance is 12 ohms; what voltage is required?

(46) A circuit has an available pressure of 220 volts; what is its resistance if a current of 40 amperes can flow through it?

(47) (*a*) What is the mechanical unit of work? (*b*) What is the electrical unit of work? (*c*) What is the relation between them?

(48) Define the joule.

(49) State the relation (*a*) between the joule and the watt; (*b*) between the coulomb and the ampere.

(50) State clearly what you understand by these four terms, i. e., joule, watt, coulomb, and ampere.

(51) Find the amount of work performed, in foot-pounds, when a current of 25 amperes flows for 2 hours, under a pressure of 100 volts.

(52) State clearly the difference between the terms power and work.

(53) Find the horsepower developed in the example of question 51.

(54) Enumerate the sources of E. M. F.

(55) Which of these are the most important?

(56) What occurs when two dissimilar metals, as zinc and copper, are immersed in a vessel containing acidulated water?

(57) What takes place when the exposed ends of the elements are connected by a wire of conducting material?

(58) Define (*a*) voltaic cell; (*b*) voltaic couple; (*c*) voltaic element.

(59) What is an electrolyte?

(60) Are zinc, carbon, and copper, electrolytes?

(61) When the electrolyte undergoes decomposition what are the decomposed parts called?

(62) Into at least how many parts must every electrolyte be decomposed?

(63) What do you understand by the word terminal?

(64) What do you understand (*a*) by the generating-plate? (*b*) by the collecting-plate?

(65) In any voltaic combination, which is the generating-plate?

(66) Define (*a*) anode; (*b*) cathode.

(67) What chemical actions take place in the voltaic cell in which the electrolyte is dilute sulfuric acid, the generating- and collecting-plates zinc and copper?

(68) What is meant by local action?

(69) What are the impurities in commercial zinc?

(70) Why do not manufacturers use pure zinc in the construction of batteries?

(71) How is local action prevented?

(72) How would you amalgamate a piece of zinc?

(73) What salt is usually added to the red-acid electrolyte to make the amalgamation more enduring?

(74) Explain what is meant by polarization and depolarization as applied to the voltaic cell.

(75) What is a depolarizer?

(76) What chemical substances are generally used in medical batteries to prevent polarization?

(77) Name the various methods employed for preventing polarization in the cell.

(78) Why does the accumulation of hydrogen on the collecting-plate transform the collecting-plate into a generating-plate?

(79) (*a*) For what purposes are primary batteries chiefly used? (*b*) What limits their use on a large scale?

(80) Enumerate the various classes of voltaic cells.

(81) Does a simple voltaic cell produce a constant current?

(82) To whom belongs the credit of constructing a voltaic cell capable of producing a constant current?

(83) (*a*) Describe fully the Grenet cell. (*b*) Explain how depolarization is accomplished in that cell.

(84) Why is the surface of the carbon element of the Grenet cell larger than the surface of the zinc element?

(85) (*a*) Describe a plunge-battery. (*b*) What is its chief advantage?

(86) Upon what principle does depolarization depend?

(87) (*a*) Why is nitric acid a good depolarizing liquid? (*b*) What objection is there to its use?

(88) How many kinds of depolarizers are there?

(89) Does the electrolyte of the cell act as a depolarizer?

(90) Describe the Daniell cell; what is its E. M. F.?

(91) Describe (*a*) the Grove cell; (*b*) the gravity cell.

(92) Give a full description of the Leclanché cell; state fully the function of the manganic dioxid used in this cell.

(93) What cell is used more than all others taken collectively in medical practice, and why?

(94) Describe the Edison-Lalande cell.

(95) What do you understand by dry cells?

(96) Have such cells an electrolyte?

(97) Describe the general construction of a dry cell.

(98) Has the ideal dry cell yet been manufactured?

(99) What are the advantages claimed for dry cells?

(100) What kind of cells should be used for cautery-work? Why?

(101) What is the ideal cell for cautery-work?

(102) State approximately the resistance of the external circuit of the cautery-battery.

(103) What, then, should be the internal resistance, in order to give maximum current-strength?

(104) Into what two general classes may accumulators be divided?

(105) Describe the construction of the original lead accumulator as made by Planté, explaining how the surface of the lead plates is increased.

(106) State the advantages of the process invented by Faure over that of Planté in the preparation of accumulator-plates.

(107) Describe briefly the several steps in the preparation of the accumulator-plates by the Faure process.

(108) What effect occurs if accumulators are discharged below 1.9 volts?

(109) How does this effect influence the utility of the accumulator?

(110) What determines the voltage and amperage of the current of an accumulator?

(111) What effect does the rate of discharge have (*a*) on the output of an accumulator? (*b*) on the life of the plates?

(112) What are the advantages of a rheostat in the circuit while doing cautery-work?

(113) How are accumulators charged?

(114) Describe the process of charging the storage-battery from a direct commercial circuit.

(115) Describe and illustrate the method of charging the storage-battery from a primary battery.

(116) How should the wires of a direct commercial current be connected to the binding-posts of the storage-battery?

(117) Is the current from the storage-battery more or less than the current used in charging it?

(118) State the percentage of the charging-current which a storage-battery yields.

(119) What precaution is necessary in connecting the poles of an accumulator?

(120) Describe briefly the method pursued in making the plates of the chlorid accumulator.

(121) How are they finally treated to form the positive and negative plates of an accumulator?

(122) What are the advantages of these plates over the paste types of plates?

(123) What are bimetallic accumulators?

(124) Describe the copper-zinc accumulator.

(125) Explain the advantages of accumulators for medical purposes where large currents are required.

(126) Define (*a*) counter E. M. F.; (*b*) ohmic resistance.

(127) How would you modify Ohm's law, $C = \frac{E}{R}$, if you were going to apply it to a circuit containing a counter E. M. F., in addition to the ohmic resistance?

(128) Show by a numerical illustration that in charging an accumulator, if the applied E. M. F. be changed by a small amount, the current will be altered in a much greater degree comparatively.

(129) What should be done to keep the current at its proper value?

(130) What is the specific gravity of the electrolyte of an accumulator in working order?

(131) What is a hydrometer?

(132) What is a voltmeter?

(133) In selecting batteries for medical purposes, what should be the objects in view?

(134) What can you say with respect to the care of batteries?

(135) What are the advantages of making one battery serve as many purposes as possible?

(136) Are oxids good or bad conductors?

(137) Why should binding-posts, connections, etc. be kept thoroughly clean and polished?

(138) Why is the upper part of the Leclanché cell coated with paraffin wax?

(139) After reading Art. **92**, do you think the Leclanché cell requires much attention?

(140) Why does an acid electrolyte cause trouble?

(141) What material is preferable to use for polishing contact surfaces and connections?

(142) How do you recognize when the bichromate cell is exhausted?

(143) If the bichromate cells are used daily, how long are they supposed to last?

(144) Describe the process of renewing the fluids of the bichromate battery.

(145) When a battery has been used, why should the electrodes be placed away in a careful manner?

(146) Should any particular attention be paid to the insulation of the rheophores? Why?

(147) How can you determine which is the positive and which is the negative pole of the battery?

(148) State, in your own words, what you understand by the term *circuit.*

(149) (*a*) When is a circuit said to be closed? (*b*) When is it said to be open?

(150) What is a grounded circuit?

(151) Define (*a*) external circuit; (*b*) internal circuit.

(152) How do you connect cells in parallel?

(153) How do you connect cells in series?

(154) What do you understand by series-parallel and parallel-series connection?

(155) Make an illustration showing 20 cells connected in parallel series, each series group containing 5 cells.

(156) Connect the above cells in series parallel, having 4 cells in each parallel group.

(157) Show by an illustration the analogy between the change of pressure in a horizontal pipe through which water is flowing and the change of E. M. F. in a conductor through which an electric current is flowing.

(158) Can an electric current flow through a circuit without a loss of pressure?

(159) (*a*) What do you understand by available E. M. F.? (*b*) What do you understand by impressed E. M. F.?

(160) A battery of cells having an E. M. F. of 10 volts on open circuit, is connected with an external circuit having a resistance of 15 ohms. Show graphically the variations in E. M. F. and in the resistance along the circuit, internal resistance of the battery not being considered.

(161) Does the current-strength change in any part of the circuit?

(162) Does the voltage change?

(163) If the voltage changes, why?

(164) What determines the current of any battery?

(165) What does the fall of potential really represent?

(166) A battery of 6 cells is sending a current through an external circuit consisting of three different resistances, viz., .2 ohm, .06 ohm, and .3 ohm. If the E. M. F. of each cell is 2 volts and the resistance 1 ohm, what will be the volume flowing through the circuit? Show graphically the variation of the E. M. F in the circuit.

(167) A current of a certain volume is sent from a main line into 4 branches, all of which leave the main line at a common point and reenter it at a common point. The resistances of the 4 branches are 1, 3, 4, and 7 ohms, respectively. If the drop of potential between the point where the branches leave the main and that at which they reenter it is 80 volts, what will be the current flowing through each branch?

(168) What do you understand by the term shunt?

(169) State the law of the divided circuit.

(170) Three conductors, *a*, *b*, and *c*, have resistances of 3, 4, and 6 ohms, respectively. If they are connected in parallel, what will be their joint resistance?

(171) What is the relation between resistance and conductivity?

(172) The individual resistances of the three branches, *a*, *b*, and *c*, of a derived circuit, are 2, 3, and 5 ohms, respectively; the sum of the currents flowing through them is 15.5 amperes. Find (*a*) the current flowing through each branch; (*b*) the E. M. F. between the two points where the branches divide and where they unite; (*c*) the combined resistance of the three branches.

(173) How may the current-volume of a voltaic cell be increased?

(174) If the individual resistances of two conductors are equal, what is their joint resistance when connected in parallel?

(175) When the individual resistances of two conductors in parallel are unequal, how do you determine their joint resistance?

(176) How do you find the joint resistance of three or more conductors in parallel?

(177) How do you find the individual current in any branch of a derived circuit?

(178) Upon what does the E. M. F. of a cell depend?

(179) A battery of 40 cells connected in series has a total E. M. F. of 60 volts and a total internal resistance of 40 ohms. Show graphically the variation of E. M. F. and the resistance along the circuit and through the battery, and the current flowing through the circuit, if the resistance of the external circuit is 210 ohms.

(180) How do you find the drop of potential in the external and internal circuit?

(181) With a battery of 50 cells, what arrangement would be used to get (*a*) the maximum E. M. F.? (*b*) the maximum current? The E. M. F. of each cell is 2 volts and its internal resistance 6 ohms.

(182) It is required to send a maximum current through an external resistance of 50 ohms by means of 400 cells, each cell having an internal resistance of .5 ohm. How should the cells be arranged?

(183) It is desired to send a current of 16 amperes through an external resistance of 22 ohms. (*a*) How many cells having an E. M. F. of 2 volts and an internal resistance of .5 ohm would be required? (*b*) How would the cells be arranged?

(184) Two hundred cells, each having an E. M. F. of 2 volts and a resistance of .5 ohm, are arranged so as to send a maximum current through an external resistance of 25 ohms. Required (*a*) the total power absorbed in the circuit; (*b*) the power absorbed in the external circuit.

(185) Show that when the external resistance is equal to the battery resistance, the power absorbed by the external circuit is one-fourth of the power which the battery develops on short circuit.

(186) Define (*a*) direct E. M. F.; (*b*) alternating E. M. F.; (*c*) pulsating E. M. F.; (*d*) continuous E. M. F.; (*e*) intermittent E. M. F. Give an example of each variety of these electromotive forces.

(187) What do you understand by (*a*) symmetrical E. M. F.? (*b*) dissymmetrical E. M. F.?

(188) Explain clearly what you understand by the terms sinusoidal or sine curve.

(189) How many alternations are there in a cycle?

(190) Give a graphic illustration of a cycle.

(191) What do you understand by a period?

(192) Define by an illustration what you understand by frequency.

(193) If a period is .01 of a second, what is its frequency?

(194) When is an E. M. F. positive and when negative?

(195) When does an E. M. F. become alternating?

(196) What are the two qualities of an E. M. F ?

(197) How many alternations are there in 100 cycles?

(198) Upon what does the number of cycles in a frequency depend?

MAGNETISM

— AND —

ELECTROMAGNETISM.

Magnetism and Electromagnetism.

(1) Define magnetism and electromagnetism.

(2) (*a*) How many kinds of magnets are there? (*b*) How many kinds of electromagnets are there?

(3) What effects are produced on a conductor through which an electric current is flowing?

(4) In how many ways may magnetism be produced?

(5) Is magnetism an inherent property of iron, steel, nickel, and cobalt?

(6) What do you know about the nature of magnetism?

(7) What do you know about the laws of magnetic action?

(8) State the law of magnetic attraction and repulsion.

(9) How are the ends of a magnetic needle designated?

(10) Show, by means of an illustration, how a freely-suspended magnetic needle will behave when brought near a magnet.

(11) Show, by an illustration, the direction of the lines of force around a bar magnet.

(12) What simple method is there for showing the direction of the magnetic lines about a magnet?

(13) Define (*a*) lines of magnetic force; (*b*) magnetic field; (*c*) magnetic flux.

(14) How many kinds of magnetic circuits are there?

(15) Upon what two quantities does the strength of every magnetic circuit depend?

(16) (*a*) What is the unit of magnetomotive force? (*b*) What is the unit of reluctance? (*c*) What is the unit of magnetic flux? (*d*) Give an equation showing the relation between these units, and state to what other equation between electrical units it is analogous.

(17) What do you understand by reluctance?

(18) What do the lines of magnetic force show?

(19) Do the lines of magnetic force actually exist?

(20) What is the medium through which magnetic force is supposed to act?

(21) How may the direction of the lines of force at any point in a magnetic field be determined?

(22) By which pole are the lines of magnetic force supposed to enter a magnet, and from which pole do they leave it?

(23) (*a*) What will take place between lines of force emanating from two south poles that face each other? (*b*) What will take place between lines of force emanating from two north poles facing each other?

(24) State the law upon which this phenomenon depends.

(25) What is meant by terrestrial magnetism?

(26) (*a*) Where is the magnetic north pole of the earth? (*b*) Where is the magnetic south pole?

(27) What important difference is there between a charge of electricity on a conductor and the magnetism of a magnet?

(28) (*a*) What is the shape of a molecule? (*b*) How does it compare with the earth in form and magnetic quality?

(29) When a piece of steel or iron is magnetized, what rearrangement takes place in the relative positions of the molecules?

(30) What is meant by induced magnetism?

(31) Show, by means of a sketch, what you understand by consequent poles.

(32) Show how you would magnetize a bar of steel or iron by means of a permanent magnet.

(33) Suppose a long bar magnet is broken into several short pieces. Show how it is that each short piece will be an independent magnet by itself, having a north and a south pole.

(34) A bar of soft iron is to be made into a magnet by means of the earth's magnetic field. What different methods can be used to temporarily break up the combinations of the molecules in the iron so that they may respond to the comparatively weak terrestrial magnetism and arrange themselves in the direction of the earth's magnetic field?

(35) What is meant by the length of a magnetic circuit?

(36) If two opposing magnetic fields are brought together, how will the lines of force arrange themselves?

(37) In what way does reluctance differ from resistance?

(38) How do the dimensions of a magnetic circuit affect the reluctance?

(39) How may magnetic circuits be classified?

(40) What is meant by the "amount" of magnetism in a magnetic circuit?

(41) What is meant by magnetic density?

(42) Do wires coiled up and conveying an electric current constitute a magnet?

(43) A bar of iron 3 inches wide and 5 inches broad has 600,000 lines of force flowing through it in the direction of its length. What is its magnetic density per square inch?

(44) A cylindrical bar magnet whose diameter is 1 inch has 22,562 lines of force passing through it. Find its magnetic density per square inch.

(45) A magnetic pole with a cross-sectional area of .5 square centimeter has 20 lines of force emanating from it. What will be the force in dynes acting upon this pole if placed at a point in a magnetic field where the density is 5,000 lines per square centimeter?

(46) Suppose an electric conductor is placed below a freely-suspended magnetic needle and parallel to it. What will happen when a current of electricity is sent through the conductor?

(47) (*a*) How can the existence of a magnetic field around a conductor conveying an electric current be proved? (*b*) How will starting and stopping the current affect the magnetic field around the conductor?

(48) Give a rule for determining the relative directions of an electric current in a conductor, and the lines of force around it.

(49) What will be the action between the fields of two parallel conductors, the currents of the conductors flowing in opposite directions?

(50) Describe a solenoid.

(51) What is the difference between a solenoid and a magnet?

(52) Can everything be imitated by a coiled wire conveying a current that can be done by a permanent magnet?

(53) Can everything be imitated by a permanent magnet that can be done by a coiled wire conveying a current? If not, why?

(54) Are magnetism and electricity inseparable?

(55) What is necessary to make the energy of a magnetic field do work?

(56) Give the rule for determining the relative directions of the current and the lines of force in a solenoid.

(57) Define permeability.

(58) Upon what does the magnetic flux through a solenoid depend?

(59) Why is the magnetic flux increased when an iron or steel core is inserted in a solenoid?

(60) Why must the wire of a solenoid be insulated?

(61) Why should the coils on a horseshoe magnet be wound in opposite directions?

(62) Make a sketch of a simple form of an electromagnet.

(63) Why is a horseshoe magnet more efficient than a straight bar magnet of the same length?

(64) Describe the iron-clad electromagnet.

(65) If a magnet is introduced into or withdrawn from a solenoid with a galvanometer in circuit, what will take place?

(66) (*a*) Give Fleming's rule for determining the direction of the induced E. M. F. in a conductor cutting across a magnetic field. (*b*) State Ampere's rule for determining the same.

(67) Under what conditions will a current flow through a conductor that is moving in a magnetic field?

(68) Upon what does the magnitude of the E. M. F. in a conductor cutting lines of force depend?

(69) Define the absolute unit of E. M. F. What is the relation between this unit and the volt?

(70) Give an equation between volts, the lines of force cut by a conductor, and the time in seconds that it takes to cut across these lines of force.

(71) Enumerate the various means of inducing an E. M. F.

(72) What do you understand by magneto-electric induction?

(73) What is the difference between magneto-electric and electromagnetic induction?

(74) Explain the phenomenon of induction.

(75) Explain the action of a magneto-electric generator.

(76) Which is the primary and which is the secondary coil of an induction-apparatus?

(77) Discuss the behavior of the magnetic field of a solenoid as the circuit is opened and closed.

(78) What are eddy, or Foucault, currents, and how are they produced?

(79) What effect have they upon metal in which they circulate?

(80) How may Foucault currents be prevented?

(81) Explain, in your own words, the operation of the primary coil shown in Fig. 49.

(82) Explain the manner in which the formation of a spark is prevented by means of a condenser when the current of the primary coil is broken.

(83) If the secondary of the induction-coil is on open circuit, how will it be affected by the "make" and "break" of the primary circuit?

(84) Under what conditions will the primary current be employed for medical purposes?

(85) How is the resistance of the external circuit reduced when the primary or extra current is used percutaneously?

(86) Is it true that more current enters the primary coil than goes out of it? Explain.

(87) Enumerate the various methods of varying the E. M. F. at the electrodes of the induction-coil.

(88) What is the shield? For what purpose is it used in the induction-coil?

(89) In the Dubois-Raymond type of induction-coil, how is the E. M. F. at the electrodes varied?

(90) (*a*) What are the methods generally employed at present of varying the E. M. F. at the electrodes of an induction-coil? (*b*) Which method do you consider preferable?

(91) Why is it that, when switch *W*, Fig. 62, is in contact with S_3, no current from coil S_2 is sent through the external circuit?

(92) What is the object of the rheostat *R* in Fig. 62?

(93) In the actual induction-coil, what is the relative position of the coil shown in Fig. 63?

(94) Why is it not possible to increase the E. M. F. of an induction-coil indefinitely by increasing the frequency of the "make" and "break" of the circuit?

(95) How is the current affected as the frequency of vibration is increased?

(96) What would be the effect on a patient if the vibrator was subject to irregularities in its movements?

(97) How may the Geissler tube be used to determine whether the E. M. F. of the coil is sufficiently high to produce the physiological effects of high-tension currents?

(98) How may the vibrator be tested for irregularities in its movements?

(99) What is the difference between the effective E. M. F. and the maximum E. M. F. of an alternating current?

(100) How may the effective current-strength of an alternating current be measured?

(101) Is a galvanometer applicable for measuring the volume of faradic currents? Give reasons for your answer.

(102) Is a graduated resistance in the secondary circuit of a faradic apparatus capable of measuring the current-volume?

(103) Of what service in electrotherapeutics is a graduated rheostat in the secondary circuit?

(104) What is the advantage of having a separate actuating force for a vibrator?

(105) Several sewing needles are hung in a bunch by threads through their eyes. How will they behave when hung over the pole of a strong magnet?

(106) In what direction do the lines of force run in a plane in which there is a single magnetic pole?

(107) Could you test your answer experimentally?

(108) Define (*a*) intensity of a magnetic field; (*b*) intensity of magnetization.

(109) A conducter is moving in a magnetic field. (*a*) Under what condition will an E. M. F. be induced in the conductor? (*b*) When will an E. M. F. not be induced in the conductor?

(110) What do you understand by the so-called extra current of the primary circuit?

(111) Explain why this extra current is so much stronger than the make-current.

(112) Having an induction-apparatus in your office, how would you proceed to determine the advantages of the break or extra current over the make-current?

ELECTROSTATICS.

ELECTROSTATICS.

(1) Define static electricity.

(2) What has given rise to the idea that there are two kinds of electricity?

(3) What is the difference in the distribution of a charge of electricity on an insulated conductor and that on a glass rod?

(4) Explain the meaning of "positively electrified" and "negatively electrified" as applied to a body having a static charge.

(5) How is the interaction of two electrically-charged bodies analogous to the interaction of two magnets?

(6) When is a body said to be charged?

(7) Explain the difference between conductors and insulators.

(8) Give three examples of (*a*) good conductors; (*b*) semi-conductors; (*c*) non-conductors, or insulators.

(9) State two of the most important laws of electricity.

(10) On what does the character of a charge depend?

(11) What do you understand by the electric series?

(12) In how many ways do charges on bodies differ?

(13) If a glass rod is rubbed with cat's fur, what is the nature of the charge on the rod?

(14) If a glass rod is rubbed with a piece of silk, what is the nature of the charge on the rod?

(15) What are the conditions requisite to produce electrification when two bodies are rubbed together?

(16) How may the presence of an electric charge on a body be detected?

(17) What is the function of the electric pendulum?

(18) State the law of the interaction of two charged bodies placed near each other.

(19) How may the charge on a body be measured?

(20) Describe (*a*) the gold-leaf electroscope; (*b*) the quadrant-electroscope; and (*c*) the torsion-balance.

(21) Define electrostatic unit of quantity of electricity.

(22) What is meant by an induced charge?

(23) Explain the meaning of the terms "free charge" and "bound charge."

(24) How is the induced charge on a body affected by the distance of that body from the inducing body?

(25) State the law of inverse squares.

(26) By means of what instrument is this law proved?

(27) What other unit of quantity can you mention?

(28) What do you consider the most important phenomenon of static electricity?

(29) Define electrostatic field.

(30) How can you explain why a neutral pith-ball is attracted by a rubbed glass rod?

(31) What will happen if two unequal charges unite, provided the charged bodies are of equal size and of the same shape?

(32) Define inductive capacity.

(33) What distinguishes dielectrics from insulators?

(34) Is it unimportant what substanee resides between two charged bodies?

(35) What substanee offers the most resistanee to induction?

(36) May a good insulator be a poor dieleetric?

(37) Are all dielectrics insulators?

(38) What conditions govern the potential of a charge?

(39) Describe the electrophorus, and explain how it can be made to eharge a Leyden jar.

(40) Upon what part of the body does the statie charge reside?

(41) Deseribe a proof-plane and its use.

(42) State the exception to the law that statie eharges reside only on the external surfaees of bodies.

(43) Does electricity in motion flow both along the surfaee and through the body of a conduetor?

(44) What limits the law that electrieity resides only on the surfaces of bodies?

(45) Is a static charge distributed uniformly over the surfaces of eondueting bodies?

(46) What do experiments show in regard to the amount of eleetrieity on the edges, corners, and flatter parts of bodies?

(47) (*a*) Will a charged sphere not exposed to the induetive influence of any surrounding bodies have its eharge evenly distributed all over its surfaee? (*b*) Will the density of the charge be uniform?

(48) (*a*) Where is the maximum density of two similarly-eharged spheres placed in contact with eaeh other? (*b*) Where is the minimum density?

(49) What effect has a decrease in the radii of eurvature of charged spheres?

(50) What will be the effect when the radii of charged spheres decrease to a point?

(51) What are necessary when it is desired to secure a rapid discharge of electrical charges?

(52) Define electrostatic capacity of a conductor.

(53) What is the unit of electrostatic capacity?

(54) What is a microfarad?

(55) The potential of a conductor is 30 volts when it has a charge of 150 coulombs. What is its capacity in microfarads?

(56) On what does the coulomb residing on a charged sphere depend?

(57) How is electrostatic capacity measured?

(58) What is necessary to know before an idea can be had of the quantity of electricity on a given conductor?

(59) What is a farad equal to?

(60) State, in the form of an equation, the relation between farads, coulombs, and volts.

(61) Explain the construction of a condenser.

(62) Of what two parts does a condenser essentially consist?

(63) Is the capacity of a conductor increased or decreased by being placed near a conductor electrified with the opposite kind of charge?

(64) Upon what does the capacity of a condenser depend?

(65) Describe the Leyden jar, and explain its action.

(66) Where is the charge of the Leyden jar located?

(67) To whom belongs the credit of locating the charge in the Leyden jar?

(68) Why does the dielectric of the Leyden jar sometimes break?

(69) What is meant by "residual charge"?

(70) Describe the construction of a battery of Leyden jars.

(71) Can an isolated charge exist?

(72) What is the objection to the electrophorus as an induction-apparatus?

(73) Into what two classes may static machines be divided?

(74) How many kinds of friction-machines are there?

(75) Are friction-machines used in electrotherapeutics at the present day?

(76) Which type of static machine is now most generally used by physicians?

(77) What purpose does the Wimshurst machine serve?

(78) What improvement did Toepler make on the Holtz machine?

(79) Describe clearly the Holtz machine and its mode of action.

(80) What voltage is required to produce an electric breeze?

(81) What is the potential difference required to send a spark between two metal balls separated by an air-gap of 1 inch?

(82) How do you estimate the maximum potential of a static machine?

(83) What is the maximum potential of a static machine when the spark-gap is $\frac{1}{2}$ inch?

(84) When you connect the prime conductors of a static machine with a piece of copper wire, what is the effect?

(85) What is the nature of a spark produced by a static discharge?

(86) What three methods are there by which a discharge can occur?

(87) What is the nature of the discharge from the Leyden jar?

(88) Explain the manner of producing static induced currents.

(89) How does an electrified body differ from a non-electrified body?

(90) Why do we regard the electric charges produced on two bodies that are rubbed together to be of opposite kinds?

(91) What is the difference between the discharge of the static machine, the discharge of the Leyden jar, and the discharge of a lightning stroke?

(92) (*a*) What is the objection to the ordinary form of Leyden jar? (*b*) How may this be overcome?

(93) What are the field-plates of the Holtz machine, and for what are they used?

(94) What is the action of the small brushes on the wire arms of the Wimshurst machine?

(95) Explain, in your own words, the principle of Thomson's replenisher.

(96) To what extent does self-induction in the circuit affect static discharges?

(97) How do you explain the fact that the collectors of an induction-machine become charged from the carriers, while they appear to be delivering charges to the carriers from the points of the combs?

(98) What is the chief reason for the inefficiency of cylinder- and plate-machines as compared with the induction-machine?

(99) Describe the means of inductively changing the potential of an insulated body from positive to negative.

(100) How do you account for the accumulation in the prime conductor of a cylinder friction-machine?

Essential Apparatus.

ESSENTIAL APPARATUS.

(1) (*a*) What are cell-selectors? (*b*) Why are they used?

(2) Explain the difference between single-handed and double-handed selectors, and state where each kind is used.

(3) What is the disadvantage of the single-handed selector?

(4) How is this disadvantage overcome?

(5) Explain how the selectors can be used as current-regulators.

(6) Which do you consider preferable as a current-regulator—a good rheostat or a good cell-selector?

(7) What is a switchboard?

(8) Describe the mercury switchboard, and state its advantages over the single-handed selectors.

(9) How do cell-selectors compare with rheostats as current-regulators?

(10) What precaution should be observed in using cell-selectors?

(11) What is the function (*a*) of the ammeter? (*b*) of the voltmeter?

(12) Upon what principle is the operation of the modern ammeter and voltmeter based?

(13) What is meant by a dead-beat instrument?

(14) Describe the practical advantage of the dead-beat instrument.

(15) How are Weston voltmeters and ammeters made dead-beat?

(16) Suppose you were going to place a Weston ammeter in a circuit through which a current of unknown strength is flowing. Would you connect your ammeter so as to give readings on the high scale (0 to 500 milliamperes) or on the low scale (0 to 10 milliamperes)? Give your reasons.

(17) How do the coils of ammeters differ from those of voltmeters with respect to their resistance?

(18) What effect on the circuit does short-circuiting a voltmeter have?

(19) Suppose a current is flowing through a circuit containing an ammeter and a voltmeter. What would be the effect of disconnecting the ammeter? What would be the effect of disconnecting the voltmeter?

(20) What are rheostats, and for what purpose are they used?

(21) What are the substances generally used for rheostats?

(22) Show, by a numerical example, the effect of a rheostat on the circuit.

(23) Rheostats of German-silver wire are now generally used in electrotherapeutic work. Can you give any reason for this?

(24) Make a rough sketch of Fig. 25, and indicate by arrows the direction of the current in the voltmeter-circuit.

(25) Explain how increasing the distance between e_1 and d_1, Fig. 24, increases the resistance of the circuit.

(26) What E. M. F. does the voltmeter in Fig. 17 indicate?

(27) Does the ammeter, Fig. 17, measure the current flowing through the battery?

(28) What E. M. F. does the voltmeter in Fig. 19 indicate?

(29) Does the ammeter in Fig. 19 indicate the total current flowing through the battery?

(30) In Fig. 30, *e* and *f* move in the same magnetic field. How can you account for the fact that the induced E. M. F. along *e* is in the opposite direction to that of *f*?

(31) Describe the commutator, and state its function.

(32) What is the function of the brushes on a dynamo-electric machine?

(33) What is the armature and what the core of the dynamo-electric machine?

(34) Why is the core of a dynamo-electric machine nearly always made of laminated iron?

(35) Explain the difference between a ring armature and a drum armature.

(36) Draw the core *b* and the poles *N* and *S*, Fig. 31. Show, on your sketch, by drawing several lines of force, *the path of the magnetic field between the two poles.* Indicate, also, by arrows, the *direction* of the lines of force.

(37) What is the difference between a self-excited and a separately-excited dynamo?

(38) What is (*a*) a shunt dynamo? (*b*) a series dynamo? (*c*) a compound dynamo? (*d*) Illustrate these dynamos by rough sketches.

(39) What difference is there in mechanical construction between a dynamo and a motor?

(40) What is the object aimed at in designing Kennelly's alternator?

(41) (*a*) What is a transformer? (*b*) In what respect does it differ from the medical induction-coil?

(42) Define (*a*) a step-up transformer; (*b*) a step-down transformer.

(43) (*a*) What is ratio of transformation? (*b*) Upon what does it depend?

(44) Where are transformers utilized in therapeutic work?

(45) What is the object of adapters?

(46) What E. M. F. is induced in a conductor when it crosses the line $x x$, Fig. 31?

(47) Give a clear and lucid explanation of the difference between electromotive force and difference of potential.

(48) What is the arbitrary zero of electric potential?

(49) What is the difference of potential between two bodies, the potentials of which are 50 volts and − 20 volts, respectively?

(50) If the current-strengths of two conductors are the same, and both are of the same specific resistance, how can the current-density be much greater in one of them?

(51) If a person is placed in an ordinary dipolar bath, and a current sent through the latter, is the current-density through all parts the same?

(52) Why is not the resistance of the bath, shown in Fig. 49, changed, if the block B is laid flat on the bottom of the tank?

(53) A tank 5 feet long, 4 feet wide, and 4 feet high, is filled with water to the height of 3 feet. Submerged in the water is a block 2 feet long, 2 feet high, and 1 foot wide, placed with its long side lengthwise. The resistance per cubic foot is 10 ohms for the water and 5 ohms for the block. Find (*a*) the resistance of the block alone; (*b*) of the water alone; and (*c*) their joint resistance.

(54) A tank 6 feet long, 4 feet wide, and 5 feet high, has a block placed lengthwise in it, as in Fig. 47. The block is practically of the same length as the tank, and is 4 feet high and 1.5 feet wide. If, now, water is run into the tank to a height of 4 feet, find (*a*) the resistance of the body alone; (*b*) the

resistance of the water; (*c*) the joint resistance of both. The resistance of the water and block is, respectively, 10 and 5 ohms per cubic foot.

(55) What is the main difference between a monopolar and a dipolar bath?

(56) If the current through a certain body is 600 milli-amperes, and the cross-sectional area is 4 square feet, what is the current-density per square foot?

(57) (*a*) How does the lowering of the water-level in a bath affect the joint resistance of body and water? (*b*) Does this reduced water-level affect the resistance of the body, and how?

(58) Suppose a tank is filled to a height of 4 feet with water, and the resistance of the latter is measured; then a block is submerged in the water, raising the height of the latter to 5 feet. The water is then drained off, reducing the depth of the water to the original 4 feet. The joint resistance of block and water is now ascertained, and from these data the resistance of the block is calculated. State whether this method is correct or not, and why.

(59) A block submerged in a tank has a joint resistance with the surrounding water of 5.5 ohms. If the resistance of the water alone is 10 ohms, what is the resistance of the block?

(60) (*a*) If a block, as shown in Fig. 51, is standing first upright and then tilted, what effect will this have on the total current-strength through the bath? (*b*) Does this new position affect the relation between the current through the block and that which flows through the adjoining water? (*c*) Has the current-density in the block been changed?

(61) What is meant by current-density?

(62) (*a*) Is the total current passing through a bath an indication of the current received by a body submerged in the water? (*b*) Does a body submerged in a bath change the total resistance of the latter by being changed from a lengthwise to a

crosswise position, if the length of the body is greater than its other dimensions? (*c*) Does this change affect the current-strength through the block itself; if so, how?

(63) (*a*) Find the current-strength through the bath in question 53, if the pressure is 10 volts. (*b*) What is the current-strength through the block?

(64) If the resistance of the water in the bath is 8 ohms and that of the body submerged in the same is 6 ohms, find (*a*) the total current passing through the bath; (*b*) the current-strength through the water alone; (*c*) the current through the body alone, if the pressure is 8 volts.

(65) (*a*) A tank 6 feet long, 4 feet wide, and 5 feet high, is filled with water to a height of 4 feet; what is the resistance of the bath, when using the cervical and foot electrodes? (*b*) If the water-level has been lowered to a height of 3 feet, what is the resistance? The resistance per cubic foot is supposed to be 10 ohms.

(66) Does a decrease of the water contained in a bath cause the body inserted in the same to receive a larger portion of the total current?

(67) After a patient was placed in a bath, the joint resistance of body and water was found to be 82.5 ohms. When the resistance of the water alone was measured, it amounted to 105.5 ohms; find the resistance of the body.

(68) If, in question 59, the water in the tank was 4 feet deep, while the joint resistance of block and water was ascertained, and if, after the block was removed for the purpose of finding the resistance of the water alone, the water-level fell to 3 feet, should any water be added to bring the water up to its former level? Give reasons for the answer.

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